UNITED STATES DEPARTMENT OF INTERIOR
GEOLOGICAL SURVEY

DESCRIPTION; MINERALOGICAL, CHEMICAL, AND ISOTOPIC COMPOSITIONS; PETROGRAPHY; DIAGENESIS; AND URANIUM-SERIES AGES OF DRILL CORES FROM THE LAGOON OF AITUTAKI, COOK ISLANDS

by

James R. Hein[1], Bruce M. Richmond[1,2], Sarah C. Gray[3],
Ruth Hausmann[4], Mitchell W. Colgan[3], Dallilah El Sabbagh[3],
and Lisa M. Gein[1]

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[1] U.S. Geological Survey, Menlo Park
[2] CCOP/SOPAC, Suva, Fiji
[3] University of California, Santa Cruz
[4] University of Köln, F.R. Germany

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INTRODUCTION

The Cook Islands were chosen for a pilot project to explore for mineral resources, especially lagoonal phosphorite, by a comprehensive program of drilling, geophysical surveys, and sampling of islands, atolls, and lagoon bottom sediments. The field program was proposed by the Cook Islands government and sponsored by the Committee for Co-ordination of Joint Prospecting for Mineral Resources in South Pacific Offshore Areas (CCOP/SOPAC). Three field seasons in three separate areas were planned. The first phase took place from 5 May to 1 July 1986 on Aitutaki, southern Cook Islands (Fig. 1 inset); the second phase took place from 6 July to 15 September 1987 on Pukapuka and Rakahanga, northern Cook Islands; and the third phase is scheduled for late 1988 on Manihiki, northern Cook Islands. Here, we describe the cores from Aitutaki (Fig. 1), present analytical data for core samples, briefly discuss the data, and comment on the mineral resource potential. Geophysical and bottom sediment data from Aitutaki will be presented in a separate U.S. Geological Survey open-file report by B. M. Richmond and others. Samples from Pukapuka and Rakahanga are presently being analyzed.

A portable floating drill rig anchored to the lagoon floor (Plate 1) was used to drill six holes (Fig. 1). All drilling equipment was provided by the Netherlands Geological Survey. The main power plant was an "Acker Ace 24" that was used to drill AQ (2.69 cm) and NQ (4.76 cm) wire-line single-wall core barrels. Seventy meters of drill pipe were available for the program. NQ pipe was used for the uppermost few meters of drilling where the sedimentary section commonly contained a mixture of coral rubble and reefal debris, and AQ was used for the remaining depth of the holes. Mud and silty mud samples were collected with a hammer core dropped down the inner core barrel after each 1 to 1.5 m of nonrecovery drilling. From the six holes drilled, 262 m of section were continuously cored and 91 m (35%) of rock and sediment were recovered (Table 1). However, more than 35% of the section actually was recovered as many large solution cavities characterize the limestone sections drilled. Penetration of the drill through these cavities and caves was calculated as no recovery. The deepest hole penetrated 69 m subbottom and the average depth per hole was 44 m. Drill locations (Fig. 1) were chosen to sample various depositional and geomorphic environments, both surface and subsurface, in the lagoon. Surface features included coral ridges, patch reefs, coral pinnacles, muddy basins, and sand flats. Subsurface (buried) ridges and depressions as determined from seismic records, were also drilled. Core was extracted from the holes after each 1.5 m of drilling and was described and logged at the drill site. Copies of these individual core logs can be provided on request.

Table 1. Core recovery in 6 holes drilled in Aitutaki Lagoon.

Hole No.	Water Depth (m)	Drilled (m)	Recovered (m)	Recovery (%)
1 + 1A	4	38.75	16.98	44
2	3	69.26	44.99	65
3	3	40.10	6.29	16
4 + 4A	2	30.72	8.05	26
5	8.5	52.86	10.23	19
6	3	29.95	4.34	14
Total	—	261.64	90.88	35

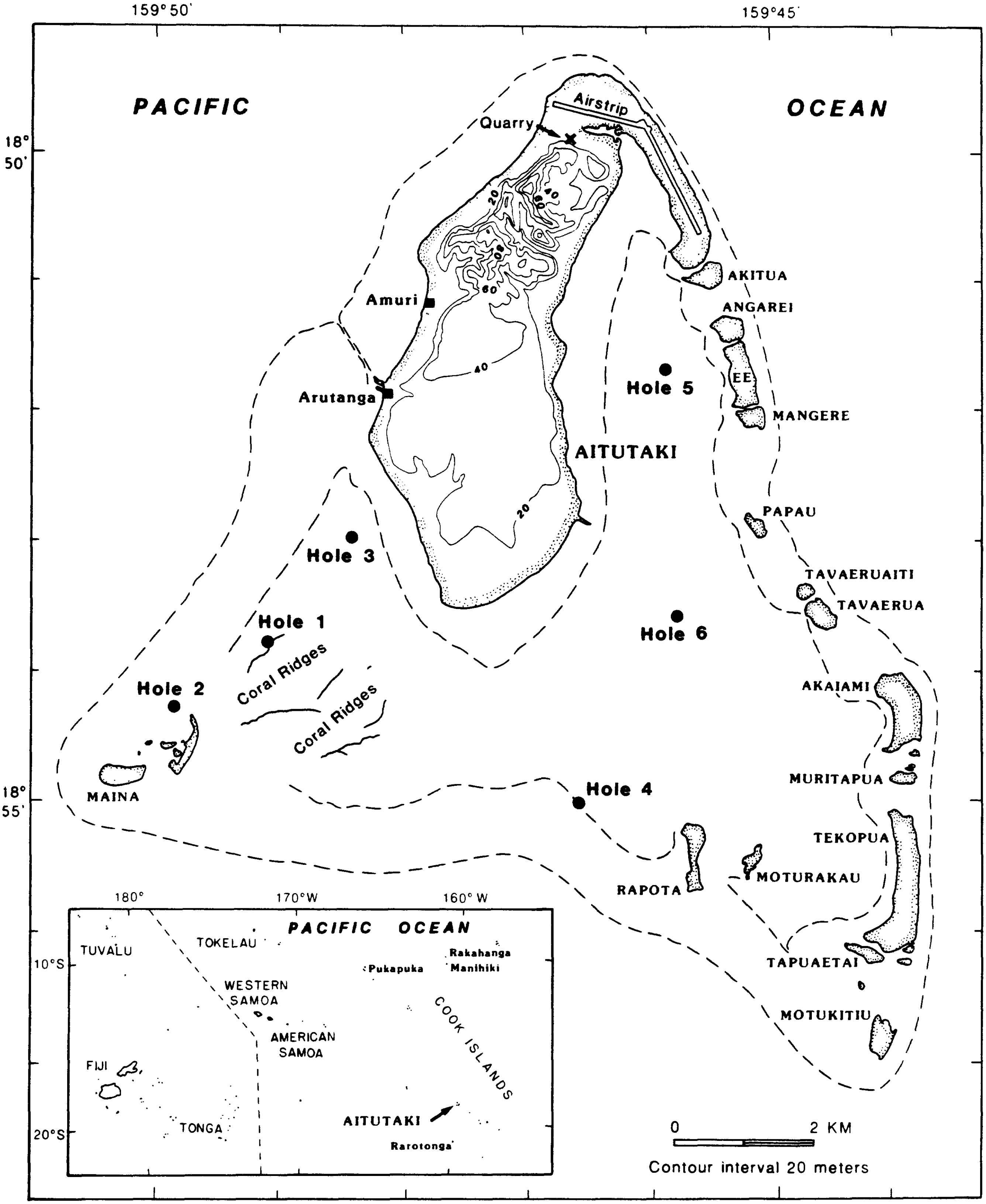

Figure 1. Location of Aitutaki almost-Atoll in the South Pacific (inset), and map of Aitutaki showing the locations of the six drill sites. Dashed lines mark the inner and outer margins of the barrier reef. The international date line is marked with a dashed line on the inset map.

Participants in the field program included:

Bruce M. Richmond, Chief Scientist, CCOP/SOPAC and U.S. Geological Survey
James R. Hein, Co-chief Scientist, U.S. Geological Survey
Edward Saphore, Electronics Technician, CCOP/SOPAC
James Kamsoo, Electronics Technician, CCOP/SOPAC
Sekove Motuiwaca, Geological Technician, CCOP/SOPAC
Oene Dijkstra, Drilling Master, Netherlands Geological Survey
Rokus Hoogendoorn, Drilling Expert, Netherlands Geological Survey

In addition, the Cook Islands government provided on-land and marine logistical support and numerous local people helped throughout various phases of the program. Significant help and guidance was provided by Stuart Kingan and Tony Utanga, and field assistance was given by Aturangi Hosking, Teriki Rongo, Vaitoti Tupa, and Bob Maoate.

GEOLOGIC SETTING

The 15 Cook Islands comprise a total land area of 241 km^2 and extend from 8° to 23° south latitudes. The islands are divided into northern and southern groups. The southern group of islands consists of a high volcanic island, Rarotonga; an almost-atoll, Aitutaki; four raised coral islands with volcanic cores, Mangaia, Mauke, Mitiaro, and Atiu; an atoll, Manuae; and a sand cay, Takutea (Wood, 1967). The northern group consists of six atolls—Palmerston, Pukapuka, Suwarrow, Rakahanga, Manihiki, Penrhyn—and a reef island, Nassau (Wood, 1967).

It has been proposed that the Cook Islands are part of a linear volcanic chain that extends from the Austral Islands in the south through Samoa and the Gilbert Islands to the Marshall Islands in the north (for example Matsuda and others, 1984). This suggested hot spot trace is postulated to have passed over the region of the mantle presently below the volcanically active Macdonald Seamount in the southern Austral Islands (Johnson, 1970; Dalrymple and others, 1975; Turner and Jarrard, 1982; Matsuda and others, 1984). However, the systematic age progression of volcanic centers expected from a hot-spot trace is not evident for some of the islands in these chains. The interaction of several hot-spot traces or a combination of genetic mechanisms is required to explain the age distribution of the islands.

Volcanic rocks from six islands in the southern Cook Islands were dated by radiometric techniques. However, volcanic rocks are not exposed in the northern group, so age dates from there are not available. Aitutaki age dates fall within two groups, 0.7 to 1.9 Ma and 6.6 to 8.4 Ma (see discussion below); Rarotonga 1.2 to 1.9 Ma; Mangaia, 13.5 to 19.6 Ma; Atiu, 5.3 to 10.3 Ma; Mauke 4.6 to 6.3 Ma; and Mitiaro 12.3 Ma (Dalrymple and others, 1975; Turner and Jarrard, 1982; Matsuda and others, 1984). These age dates attest to the episodic nature of volcanism in the Cook Islands, and to the need for analysis of additional samples, especially samples dredged from the flanks of the northern atolls, to get a more complete picture of the volcanic evolution of the Cook Islands.

Aitutaki is an almost-atoll (Stoddart and Gibbs, 1975; also called near-atoll) because, in the strict sense, it has not yet evolved into an atoll, which consists of a barrier reef—with or without sand islands—enclosing a lagoon. Rather, Aitutaki consists of a triangular-shaped barrier reef with a relatively large volcanic island located in the northwest part of the lagoon (Fig. 1). Sand motus (islets) cap the east and southwest reef flats and two volcanic motus, Rapota and Moturakau are located in the southeast corner of the lagoon (Fig. 1). The outer edge of the barrier reef encloses an area of 98 km^2 that includes a 39 km^2 shallow lagoon, 16 km^2 main volcanic island, and 43 km^2 reef flat (barrier plus fringing reefs). Aitutaki volcanic island is bordered by a fringing reef.

The main volcanic island is made up of basalt flows, volcaniclastic and pyroclastic rocks, and is fringed by Holocene carbonate sand. Volcanic rocks include alkali olivine basalt, olivine nephelinite, basanite, highly altered vesicular to amygdaloidal basalt located on the southwest shore, and rare trachyte and phonolite. Some flows, especially those at the quarry (Fig. 1), contain large ultramafic xenoliths of augite and lherzolite. Turner and Jarrard (1982) suggested the following volcanic chronology for Aitutaki. A shield volcano built up to sea level in the late Miocene and by 8 Ma, both alkalic basalt and nephelinite were being erupted. This early phase of volcanism apparently was followed by 6 m.y. of volcanic quiescence, at which time subsidence, erosion, and extensive reef growth occurred. At about 1.9 Ma volcanism began again and continued until about 0.7 Ma. Basalt flows recovered by this drilling program indicate that volcanism has occurred within the past 0.2 Ma.

No makatea (raised reef) occurs on Aitutaki. Coastal areas around the main island consist of carbonate sand, rocky benches (basalt flows), conglomerate, beach rock, and reef flats. The sediment-floored lagoon is characteristically shallow, averaging 3 m to 5 m deep; a series of enclosed basins in the eastern lagoon are as much as 10 m deep. The lagoon is dotted with coral knolls, pinnacles, and patch reefs. The southwest part of the lagoon contains numerous irregular to sinuous coral ridges.

RESULTS

For convenience, lithologic, chemical, isotopic, mineralogic, and petrographic data and a brief summary of the data will be presented for each hole, and a compilation of all data for all the holes together is presented in four appendices. The data are integrated and discussed in the discussion section. Photographs and photomicrographs are presented as plates in the back of this paper.

Sixty-one thin sections of cores from the six holes drilled were examined under a petrographic microscope using plain-polarized and cross-polarized light. We characterized the major constituents in order to determine their origin and diagenetic history. The following features were systematically described:

Carbonates: 1) Mineralogy, 2) Identification, composition, and abundance of framework grains and clasts, 3) Nature and possible origin of cements/matrix, 4) Degree and classification of porosity, based on Choquette and Pray, 1970, 5) Structures, 6) Diagenesis, 7) Other interesting features, 8) Classification, based on both Dunham (1962) and Folk (1962).

Basalts: 1) Mineralogy, 2) Texture, 3) Degree of alteration.

The mineralogy listed with the petrographic descriptions is based on results from x-ray diffraction and is taken from Appendix 1.

HOLES 1 AND 1A

Hole 1 is located in the western lagoon about half way between the south point of Aitutaki Island and Motu Maina (islet). It was drilled about 4 m from the edge of a sinuous coral ridge (Fig. 1), that is about 8 m wide, 4 m high, and over 1 km long. After about 4 m of penetration, the hole was abandoned and respudded about 1 m away in order to try to get better recovery in the upper section of coral rubble. 38.75 m were drilled and 16.98 m were recovered (44%; Table 1). The water depth is 4 m.

Lithology

The uppermost 5 m of section consist of alternating layers of reefal debris—sand and gravel—and framework reefal limestone (Fig. 2). Some sand layers are size graded. Between 5 and 13 m subbottom depth occur framework reefal limestone and bioclastic limestone interbedded with either reefal sand and/or alternating with solution cavities (no recovery zones). This interpretation is based on the no recovery intervals (see Fig. 2) in the 5 to 13 m depth range having coincided with dramatic drops in water pressure while drilling, a result of either sand washing out of the hole or of the presence of solution cavities. We suppose that sand layers are common in this depth interval. Below about 13 m diagenesis becomes significant, with thick intervals (centimeters to a decimeter) of pure sparry calcite cement at about 17 m and 20 m subbottom. From 13 m to 30 m, framework reefal limestone and bioclastic limestone alternate with narrow solution cavities and probably some sand layers. From 30 m to 35 m there occurs a series of poorly consolidated, in places reversely graded, lapilli tuffs(?), with bedding-parallel and crosscutting orange goethite veins and bedding-parallel sparry calcite layers. A thin, subaerially erupted alkalic basalt flow with clinopyroxene xenoliths and calcite veins occurs in this depth interval. Between 35 m and 37 m exists a series of black to gray altered ash beds, volcaniclastic siltstone and mudstone, and completely subaerially weathered basalt flows. Weathering occurred under tropical to subtropical conditions causing intense leaching of the deposits. Drilling stopped in an alkalic basalt flow veined with calcite and containing ultramafic xenoliths (Plate 3A). This basalt probably is volcanic basement.

Mineralogy

The 30 m limestone section is divided into three stratigraphic intervals based on mineralogy (Table 2). Aragonite (skeletal material) is predominant down to 8 ±1.5 m subbottom depth, where an interval of predominantly calcite with moderate to minor amounts of aragonite begins and extends to 16 m. Calcite is the only carbonate mineral that occurs below 16 m. All calcite, whether sparry calcite cement or replaced skeletal material is low-magnesium calcite (Table 3).

The volcanogenic section consists of a complex array of primary minerals and secondary minerals produced by moderate to intense chemical leaching of the deposits under tropical to subtropical conditions. Pyroxene, plagioclase, and magnetite are primary minerals. Kaolinite is the dominant clay mineral. Olivine, some pyroxene, and some magnetite altered into a variety of iron minerals including goethite, lepidocrocite, and possibly hematite. The secondary minerals are characteristically poorly crystalline and a variety of mixed-layer clay minerals and probably x-ray amorphous phases occur; these crystallinity characteristics are typically developed during soil-forming processes.

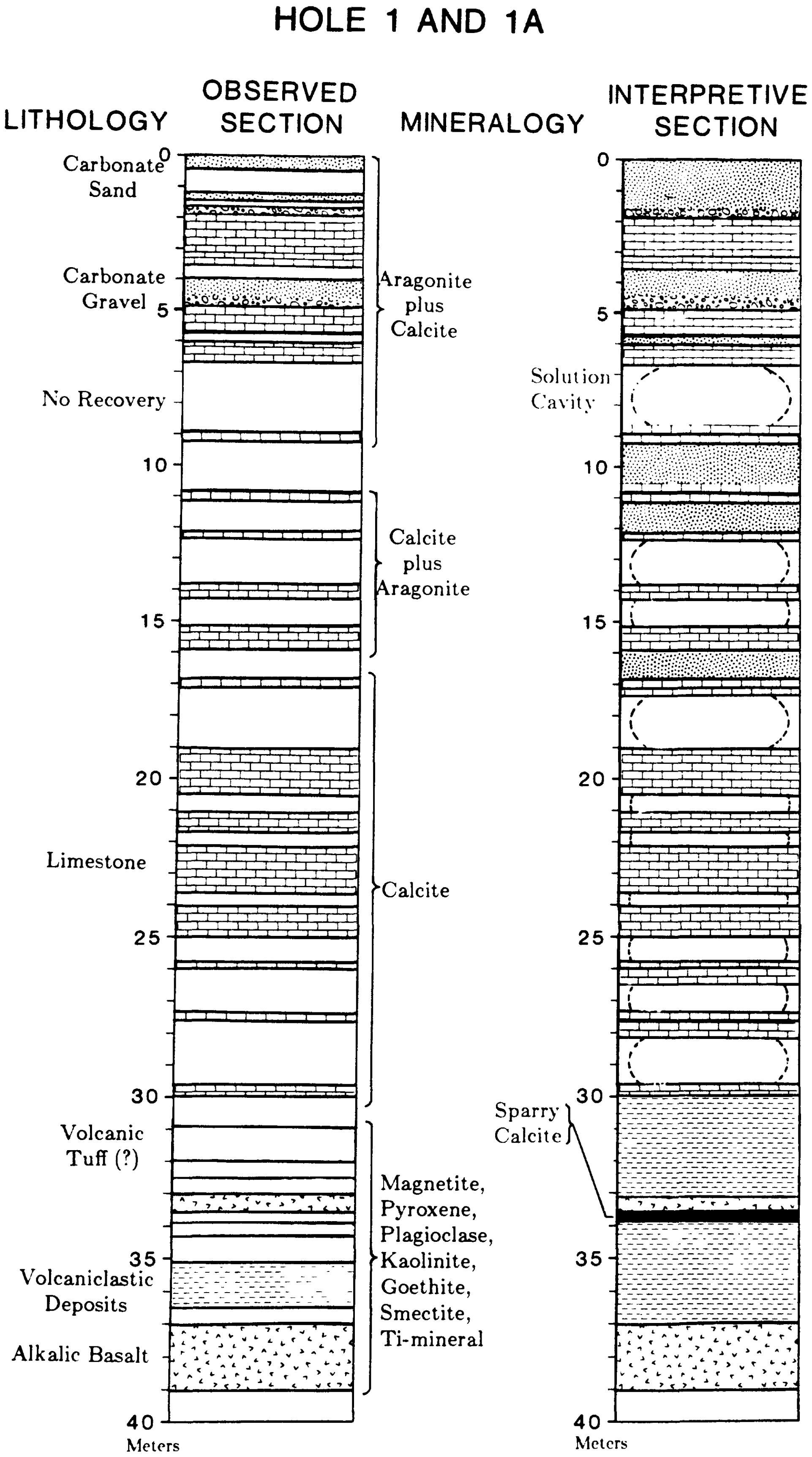

Figure 2. Stratigraphic section, general mineralogy corresponding to each lithology, and interpretive section for Holes 1 and 1A.

Table 2. Mineralogy determined by x-ray diffraction for drill cores from Hole 1A, Aitutaki, Cook Islands.

Sample No.[1]	Major[2]	Moderate	Minor or Trace
1A-4-345	Aragonite		Calcite
1A-5-497	Aragonite		Calcite
1A-5-501	Aragonite	Calcite	trace of other carbonates
1A-7-653	Aragonite		
1A-9-944	Calcite		Aragonite
1A-10-1085	Calcite		
1A-13-1507	Calcite	Aragonite	
1A-13-1530	Calcite		Aragonite
1A-14-1705	Calcite		
1A-14-1707	Calcite		
1A-16-1960-I	Calcite		
1A-16-1960-II	Calcite		
1A-16-2008A	Calcite		
1A-16-2008B	Calcite		
1A-19-2432	Calcite		
1A-21-2765	Calcite		
1A-21-2773	Calcite		
1A-23-3120A	Kaolinite	Goethite Anatase	Lepidocrocite Smectite
1A-23-3120B	Kaolinite	Anatase	
1A-23-3120C	Magnetite	Kaolinite	
1A-24-3251	Calcite		
1A-25-3295-I	Calcite		
1A-25-3295-II	Pyroxene	Calcite	
1A-25-3295-III	Calcite Pyroxene	Goethite	Smectite Mixed layer clay minerals
1A-25-3295-IV	Pyroxene	Calcite Smectite	Mixed layer clay minerals
1A-25-3295-V	Pyroxene	Plagioclase Calcite	Smectite Mixed layer clay minerals Celadonite?
1A-25-3306	Calcite		Smectite
1A-25-3330	Magnetite	Smectite Goethite Calcite Kaolinite	Mixed layer clay minerals Celadonite? Apatite?
1A-26-3487	Magnetite	Smectite Goethite	Kaolinite Calcite Celadonite Mixed layer clay minerals Pyroxene Apatite? Maghemite?

Sample No.[1]	Major[2]	Moderate	Minor or Trace
1A-26-3498	Calcite	Magnetite Goethite Smectite	Mixed layer clay minerals Kaolinite Plagioclase Pyroxene Apatite? Maghemite?
1A-26-3531	Magnetite	Calcite Smectite Goethite Pyroxene	Mixed layer clay minerals Kaolinite Plagioclase Apatite? Maghemite?
1A-26-3545	Magnetite	Goethite Smectite Plagioclase Pyroxene Calcite	Apatite? Celadonite? Maghemite?
1A-26-3547	Calcite	Magnetite Pyroxene Plagioclase Smectite Goethite	Celadonite? Apatite?
1A-26-3549	Calcite	Magnetite Pyroxene Plagioclase Smectite Goethite	Mixed layer clay minerals Apatite?
1A-28-3644	Pyroxene	Calcite	Smectite
1A-28-3653	Magnetite Pyroxene	Smectite Plagioclase Goethite	Mixed layer clay minerals Apatite? Maghemite?
1A-30-3825	Calcite		
1A-30-3873	Magnetite Pyroxene Plagioclase	Smectite Goethite	Hematite? Apatite?

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[1] First number in sample number is hole number; second number is core number; third number is distance in centimeters from top of hole (seafloor).

[2] Roughly, major is >25%, moderate is 5-25%, and minor or trace is <5% (weight percent).

Table 3. Mole percentage $MgCO_3$ in carbonates from Hole 1A, Aitutaki, Cook Islands.

Sample No.	Mole % $MgCO_3$	Mineralogy
1A-10-1085	1	Calcite
1A-13-1507	1	Calcite
1A-13-1530	1	Calcite
1A-14-1705	0	Calcite
1A-14-1707	0	Calcite
1A-16-1960-I	0	Calcite
1A-16-1960-II	0	Calcite
1A-16-2008A	0	Calcite
1A-16-1008B	0	Calcite
1A-19-2432	0	Calcite
1A-21-2765	0	Calcite
1A-21-2773	1	Calcite
1A-24-3251	1	Calcite
1A-25-3306	1	Calcite
1A-30-3825	0.5	Calcite

Chemical Composition

The limestones are relatively pure calcium carbonate (Table 4). The aragonite-rich limestones have high amounts of magnesium and strontium, which are significantly reduced when aragonite is replaced by calcite.

The volcanogenic rocks are high in oxidized iron, titanium, chromium, and nickel. The volcaniclastic and pedogenic deposits are especially high in titanium and chromium, which were concentrated from leaching of volcanic debris rich with titanium-chrome magnetite, titanaugite, and ultramafic xenoliths.

Table 4. Chemical composition of reefal limestones (columns 1-4), and volcanogenic rocks and sediments (columns 5-8) from Hole 1A, Aitutaki, Cook Islands.

	1A-4-345	1A-10-1085	1A-16-1960	1A-21-2765		1A-23-3120	1A-26-3487	1A-28-3653	1A-30-3873
SiO_2 (wt. %)	<0.10	0.66	0.40	0.54	SiO_2 (wt. %)	28.4	31.9	35.5	40.4
Al_2O_3	0.21	0.23	0.35	1.01	Al_2O_3	23.5	18.6	13.8	16.7
Fe_2O_3	—	—	0.08	0.30	Fe_2O_3	23.1	16.8	11.7	14.4
FeO	3.00	0.05	<0.02	0.05	FeO	0.64	2.14	2.09	2.65
MgO	1.58	0.92	0.38	0.48	MgO	0.89	1.53	2.70	4.13
CaO	52.4	55.6	56.3	55.2	CaO	0.29	5.66	11.5	3.11
Na_2O	0.40	0.12	0.07	0.12	Na_2O	1.34	1.23	1.64	1.60
K_2O	<0.02	<0.02	<0.02	<0.02	K_2O	0.13	0.51	1.14	1.68
TiO_2	<0.02	0.01	<0.02	0.19	TiO_2	4.52	3.74	2.73	3.35
P_2O_5	0.05	0.07	0.06	0.17	P_2O_5	0.47	1.13	0.79	0.93
MnO	0.001[‡]	0.004[‡]	0.003[‡]	0.008[‡]	MnO	0.07	0.11	0.21	0.23
H_2O^-	0.22	0.01	0.01	0.06	H_2O^-	3.66	5.28	4.78	4.26
H_2O^+	1.46	0.25	0.28	0.71	H_2O^+	9.47	6.66	3.48	4.82
CO_2	41.3	44.8	44.6	43.9	CO_2	0.22	2.91	6.30	0.09
LOI	44.8	43.7	43.2	43.2	LOI	16.5	16.7	16.4	10.6
Total[†]	102.44	101.36	100.84	101.27	Total[†]	99.85	100.05	100.20	99.78
Ba (ppm)	9	8	10	16	As (ppm)	<10	<10	<10	<10
Ce	<4	<4	<4	10	Ba	150	140	520	560
Co	1	2	2	3	Be	4	2	2	2
Cr	3	9	11	30	Cd	<2	3	3	3
Cu	2	2	2	3	Ce	42	110	96	120
La	<2	<2	<2	2	Co	50	48	86	87
Li	<2	<2	<2	3	Cr	1300	1000	640	820
Mo	<2	<2	<2	<2	Cu	61	78	55	69
Nd	<4	<4	4	7	Eu	2	5	4	5
Ni	2	5	7	20	Ga	39	31	24	27
Sc	<2	<2	<2	3	La	29	67	52	69
Sr	6300	1000	640	900	Li	93	41	24	54
V	8	4	4	10	Mo	3	<2	<2	<2
Zn	4	4	6	8	Nb	64	31	39	41
					Nd	21	63	52	68
					Ni	670	510	390	480
					Pb	16	10	9	14
					Sc	47	31	24	30
					Sr	230	160	390	400
					Th	16	11	8	11
					V	320	220	170	190
					Y	34	36	31	44
					Yb	3	3	3	3
					Zn	200	190	130	180
Lithology	reefal limestone	gray and white reefal limestone	gray reefal limestone	gray-brown reefal limestone	Lithology	dark gray altered tuff(?) with orange veins, pedogenic	dark gray completely altered volcanic rock, pedogenic	altered alkalic basalt with calcite veins	relatively fresh alkalic basalt

All analyses were performed by U.S. Geological Survey analytical laboratories in Denver, Colorado and Menlo Park, California. Ten major oxides analyzed by wavelength dispersive x-ray fluorescence spectroscopy, Denver and Menlo Park. Analytical expertise provided by J. Taggart, A. Bartel, D. Siems, R. Lerner, B. King, D. Vivit, and M. Dyslin. Minor and trace elements analyzed by inductively coupled plasma atomic emission spectroscopy, Denver. Analytical expertise provided by P. Briggs, and B. Anderson. FeO, CO_2, and water determined by wet chemical methods, Menlo Park. T. Fries, L. Espos, and S. Neil provided analytical expertise.

— not detected.

[†] Totals based on LOI (loss on ignition) at 900 °C.

[‡] Value reported is from emission spectroscopy data.

For the four carbonate samples the following elements were analyzed but were below detection limits (in ppm): Ag <2; As <10; Au <8; Be <1; Bi <10; Cd <2; Eu <2; Ga <4; Ho <4; Nb <4; Pb <4; Sn <10; Ta <40; Th <4; U <100; Y <2; and Yb <1.

For the four volcanic and sediment samples the following elements were analyzed for but were below detection limits: Ag <2; Au <8; Bi < 10; Ho <4; Sn <10; Ta <40; U <100.

Stable Isotopic Composition of Calcite

Secondary calcites have $\delta^{13}C$ values between $-9.1^{0}/_{00}$ and $-12.0^{0}/_{00}$, averaging $-10.7^{0}/_{00}$, and $\delta^{18}O$ between $24.7^{0}/_{00}$ and $25.2^{0}/_{00}$, averaging $24.9^{0}/_{00}$ (Table 5). The 8 analyses are from depths between 17 m and 38 m yet all values are closely comparable. No trend with stratigraphic position is evident. $\delta^{13}C$ values indicate that organic matter and seawater (probably via the dissolution of biogenic carbonate that originally precipitated from seawater) were both sources for the carbon, and that formation of the secondary calcite was in a predominantly freshwater environment.

Table 5. Carbon and oxygen isotopic compositions of calcite cements and veins from Hole 1A, Aitutaki, Cook Islands.

Sample No.	$\delta^{13}C$ PDB	$\delta^{18}O$ SMOW	Mineralogy	Sample Description
1A-14-1705	-12.0	24.8	Calcite	coarse-grained sparry calcite cement
1A-14-1707	-9.1	24.7	Calcite	same as above
1A-16-2008A	-10.7	25.0	Calcite	dog-tooth spar calcite layer above 2008B
1A-16-2008B	-11.3	24.7	Calcite	sparry calcite layer
1A-19-2432	-10.1	24.9	Calcite	coarse-grained dog-tooth spar calcite in vug
1A-24-3251	-10.4	24.9	Calcite	sparry calcite layer within tuff section
1A-25-3306	-10.4	25.0	Calcite	sparry calcite layer below basalt and above tuff
1A-30-3825	-11.2	25.2	Calcite	calcite layer within basalt
Average calcite	-10.7	24.9		

Analyses performed at U.S. Geological Survey isotope laboratory by Doug White.

Uranium-Series Age Dates

Uranium content is higher and thorium content lower (Table 6) than average values (2.2 ppm and 1.7 ppm respectively; Turekian and Wedepohl, 1961) determined for carbonate rocks. The apparent age determined for the recrystallized limestone (1A-13-1507) is much too old and probably reflects U-Th mobilization during diagenesis; the relatively high $^{230}Th/^{232}Th$ precludes the presence of detrital minerals as an influence on the age of the limestone. The apparent age of the limestone at 6.5 m subbottom depth is incompatible with known global sea level positions since the last glacial maximum at 18 ka (Table 6). This age implies that living coral existed 20 to 100 m above sea level, clearly untenable. The uppermost apparent age determined from a limestone at about 5 m indicates a rapid average vertical growth rate of 5 m/ka; if this rate is extrapolated to the base of the limestone section at 30 m, coral growth would have begun at about 6,000 years ago. Calculations based on the thickness of Holocene deposits determined from seismic-reflection records gives an average vertical growth rate of about 2 m/1,000 years, which would indicate initiation of coral growth at about 15,000 years ago. Solution unconformities representing significant time periods, the cessation of coral growth as the result of reductions in water temperature, or other biological and oceanographic conditions (e.g., El Niño, *Acanthaster* explosions) could complicate the interpretation of the calculated and extrapolated ages.

Table 6. Uranium and thorium contents and U-series apparent ages of coral from Hole 1A, Aitutaki, Cook Islands.

Lab No.	Field No.	U ppm	Th ppm	$\frac{^{234}U}{^{238}U}$	$\frac{^{230}Th}{^{232}Th}$	$\frac{^{230}Th}{^{234}U}$	U/Th age 1,000 years	Corrected age 1,000 years	Coral Types and Comments	Mineralogy (XRD)*
637	1A-5-497	4.268±0.150	1.207±0.154	1.157±0.044	1.108±0.187	0.089±0.011	$10.0^{+1.3}_{-1.2}$	$1.0^{+1.2}_{-1.0}$	*Porites*	A(c)
638	1A-5-501	—	—	—	—	—	recent	—	No Th detected	A(C)
639	1A-7-653	3.177±0.101	0.044±0.043	1.119±0.029	38.327±38.448	0.154±0.015	$18.1^{+1.9}_{-1.8}$	$17.7^{+1.9}_{-1.8}$	*Porites*	A
640	1A-13-1507	2.986±0.112	0.229±0.061	0.991±0.033	44.285±11.682	1.124±0.070	≥202	—	Recrystallized reefal debris	C(A)

*	Major	Moderate	Minor or Trace
Aragonite	A	(A)	(a)
Calcite	C	(C)	(c)

Petrography

Hole 1A Core 4 Depth 3.45 m
Mineralogy (XRD): Aragonite; minor calcite.
Classification: Coral Boundstone, Coral Biolithite.

Unaltered framework coral is dominant. A thin layer of fine-grained pellets of clastic micrite marks the contact between two generations of coral growth. Some pores are lined by fibrous isopachous aragonite cement indicating submarine cementation. Pellets of clastic micrite and carbonate skeletal fragments infill some pores. Growth-framework porosity is moderate.

Hole 1A Core 10 Depth 10.85 m
Mineralogy (XRD): Calcite.
Classification: Bioclastic Packstone, Biomicrite.

Skeletal fragments are surrounded by fine- to coarse-grained clastic micrite (Plate 4A). Bioclastic grains include fragments of calcareous red algae, echinoderms, bivalves, benthic foraminifera (nummulites and miliolids), gastropods, bryozoa, and worm tubes. Minor pellets occur. Neomorphism of skeletal grains to sparry calcite, clastic micrite to microspar, and void-filling sparry calcite cementation are evident (Plate 4B). Porosity is high with megapore vugs > interparticle > intraparticle.

Hole 1A Core 13 Depth 15.30 m
Mineralogy (XRD): Calcite; minor aragonite.
Classification: Boundstone, Coral Biolithite.

This complex sample is composed of coral and bioclastic calcarenite. Peloids are either micritized bioclasts or clastic micrite that was lithified before being reworked. Coral, benthic foraminifera, a complete gastropod (Plate 5A), bryozoa, and serpulid worm tubes are identifiable. The gastropod and coral underwent neomorphism and the coral pores were infilled by freshwater phreatic void-filling sparry calcite. Intra- and intergranular pores and vugs produce moderate porosity.

Hole 1A Core 16 Depth 19.60 m

Mineralogy (XRD): Calcite.
Classification: Skeletal Grainstone, Biosparite.

Highly altered skeletal fragments of bivalves, calcareous red algae, echinoderms, and benthic foraminifera are surrounded by a coarse-grained calcilutite matrix made up of rounded to subangular grains. Bivalve skeletal grains underwent neomorphism, but retain faint outlines of the internal wall structure (Plate 5B). At least two episodes of cementation are apparent. Faint rims of fibrous marine phreatic cement precipitated first and were followed by more extensive cementation with void-filling freshwater sparry calcite. Porosity is abundant: vuggy > moldic.

Hole 1A Core 21 Depth 27.65 m
Mineralogy (XRD): Calcite.
Classification: Boundstone, Coral Biolithite.

Altered coral is the predominant bioclast (Plates 6A,B). Two thin layers of microspar within the coral indicate a hiatus in coral growth. The majority of the coral was partly dissolved and subsequently infilled by sparry calcite, but a few patches of calcite underwent neomorphism. Pores in the coral were also filled with sparry calcite. Where pores are partly empty the sparry calcite terminates into well-formed scalenohedral crystals. Cementation occurred within the freshwater phreatic zone. Porosity is moderate and vuggy.

Hole 1A Core 25 Depth 32.95 m
Mineralogy (XRD): Major pyroxene; moderate plagioclase, calcite; minor smectite, mixed-layer clay minerals.
Classification: Alkali Olivine Basalt.

Altered aphanitic basalt contains small plagioclase laths and clinopyroxene phenocrysts in a glass groundmass, now altered to clay minerals. Large orange-brown phenocrysts were olivine crystals that completely altered to goethite. Minute opaque crystals, probably magnetite, are ubiquitous. Thin veins of calcite anastomose through the sample. The void-filling sparry calcite indicates precipitation in a freshwater phreatic zone. The basalt erupted subaerially and contains a clinopyroxenite xenolith.

Hole 1A Core 28 Depth 36.60 m
Mineralogy (XRD): Major magnetite, pyroxene; moderate smectite, plagioclase, goethite; minor mixed-layer clays.
Classification: Alkalic Basalt.

Altered aphanitic basalt contains small plagioclase laths and clinopyroxene phenocrysts in a groundmass of glass altered to smectite. Large olivine crystals altered to orange-brown masses of goethite. Small grains of magnetite are ubiquitous. Thin veins of void-filling, sparry calcite are present. The basalt erupted subaerially.

Hole 1A Core 30 Depth 38.64 m
Mineralogy (XRD): Major magnetite, pyroxene, plagioclase; moderate smectite, goethite.
Classification: Alkalic Basalt.

Altered aphanitic basalt comprises small plagioclase laths and clinopyroxene phenocrysts in a groundmass of glass altered to smectite. Large orange-brown phenocrysts, originally olivine crystals, are now goethite. Small crystals of magnetite are ubiquitous. Thin veins of void-filling sparry calcite are present. The basalt probably erupted subaerially.

Summary of Holes 1 and 1A

Holes 1 and 1A consist of 30 m of limestone and carbonate sediment that overlie about 9 m of volcanogenic sediments, probably pyroclastic and volcaniclastic deposits and alkalic basalt flows. These volcanic rocks were altered and leached during soil-forming processes. Echinoderms, mollusks, foraminifera, and bryozoans occur throughout the carbonate section with framework coral most common in the upper and lowermost parts of the section (Table 7). Diagenesis increases with depth and is reflected by the carbonate mineralogy, cement, and porosity. The section is divided into four stratigraphic zones, three in the carbonate section that are based on mineralogy and diagenesis, and one volcanogenic section.

Zone 1, 0 to 8 m, is composed of primary skeletal aragonite, minor acicular aragonite cement, and growth-framework and intragranular porosity. The Sr content is high in the aragonite.

Zone 2, 8 to 16 m, is composed of calcite with minor aragonite. Diagenesis produced freshwater void-filling cements and neomorphism of calcite. Moderate porosity results from primary intra- and intergranular pores and secondary molds and vugs. Sr content decreased with the conversion of aragonite to calcite. Oxygen and carbon isotopic compositions of calcite cement indicate formation in freshwater with organic matter and seawater as the sources of carbon.

Zone 3, 16 to 30 m, is composed of calcite with freshwater and marine phreatic void-filling cements and neomorphism of calcite. Abundant secondary porosity was produced by the dissolution of grains and cement. The isotopic composition of cements is the same as those in zone 2.

Zone 4, 30 to 38 m, consists of volcanogenic deposits and minerals and weathering products of these deposits. Calcite veins and layers within this section formed under the same conditions as the cements in the limestone sections, and veins contain void-filling freshwater phreatic calcite. Subaerially erupted alkalic basalt flows were preceded by pyroclastic and/or volcaniclastic deposition. Tropical or subtropical chemical leaching produced pedogenic deposits rich in titanium and chromium.

Table 7. Summary of petrography, Hole 1A.

Geology

Depth (m)	Mineralogy	Major Diagenetic Fabrics	Minor Diagenetic Fabrics	Major Porosity Types	Minor Porosity Types	Degree of Porosity
3.45	A>>C	AA		GF	I	M
10.85	C	VF	N	V	I,i	A
15.3	C>>A	VF/fp	N	I	i	M
19.6	C	VF/fp,mp	N	V	M	A
27.65	C	VF/fp,mp	N	V	—	M
32.95	S,I,C,K	—	VF/fp	—	—	—
36.6	S,I,K	—	VF	—	—	—
38.64	S,I,K	—	VF	—	—	—

Biology

Depth (m)	Coral	Algae	Mollusks	Echinoderms	Bryozoa	Foraminifera
3.45	*	—	—	—	—	—
10.85	—	*	*	*	*	*
15.3	*	—	*	—	*	*
19.6	—	*	*	*	—	*
27.65	*	—	—	—	—	—

Key to Table 7

Mineralogy:
- C: Calcite
- A: Aragonite
- S: Silicates
- K: Clay minerals
- I: Iron minerals

Cements: Type/Origin

Type:
- VF: void-filling sparry calcite
- N: neomorphically derived sparry calcite
- AA: aragonitic

Origin:
- mp: marine phreatic
- fp: freshwater phreatic

Porosity: Degree/Development

Development:
- M: moldic
- GF: growth framework
- V: vuggy
- I: intraparticle
- i: interparticle

Degree:
- Abundant porosity: A
- Moderate porosity: M

Biota:
- * abundant
- X present
- — absent

HOLE 2

Hole 2 is located near the inner edge of the barrier reef flat and adjacent to a mobile sand bar associated with Motu Maina (Fig. 1). The site was chosen in order to sample a seismically defined subsurface domal structure that has no topographic expression. The water depth is 3 m.

Lithology

The uppermost 12 m of section consist of three basic interbedded lithologies: coral framework limestone (Plates 2A, 2B), bioclastic limestone (Plate 2A), and carbonate sand (Fig. 3). Most of the nonrecovery intervals are probably carbonate sand layers that washed from the drill pipe. Between 12 m and 38 m subbottom, framework reefal limestone predominates and is interbedded with bioclastic limestone and solution cavities. The drill string dropped through a 1.7 m solution cavity (28 m to 30 m, Fig. 3) that is floored by 1 m of mud formed by subaerial leaching and soil development on a karst surface. Most of the nonrecovery intervals in this section (Fig. 3) are probably solution cavities, some also floored by mud as indicated by mud on the extracted core barrels. Also in the 12 to 38 m depth interval are sparry calcite layers up to 10-cm thick with calcite crystals up to 3-cm long (Plate 2B). These layers occur about every 0.5 to 1.5 m throughout this section. Below 40 ±1 m, dolomite replaced the limestone thereby producing dolostone. Core recovery in the dolostone section was excellent. Thin, laminated, volcanic ash(?) layers or hydrothermal iron deposits occur at 43.25 m, 44.20 m, and 60.04 m subbottom depths. The lowermost 10 m of section contain intervals of mottled brown and gray (Plate 3B). Colors vary from pale to dark brown, pale orange, to yellowish orange. The brown layers higher in the section and the brown mottled areas near the base of the cored section probably result from volcanic activity, either through the deposition of volcanic ash or by precipitation of iron oxyhydroxide from submarine low-temperature hydrothermal plumes. The latter explanation is supported by the fact that only an increase in iron content distinguishes the brown areas. We would expect increases in silicon, aluminum, etc., if ash were responsible for the brown colors, unless all elements other than iron were leached or removed during alteration and dolomite replacement, which is unlikely.

Mineralogy

The 69-m carbonate section sampled at Hole 2 consists of three mineralogic zones: aragonite with calcite, 0 to 10 m; calcite, 10 to 40 m; and dolomite, 40 to 69 m (Table 8). All the calcite is low-magnesium calcite and all the dolomite is protodolomite with an excess of 3 to 10 mole percent $CaCO_3$ and weak and broad x-ray reflections at 2.41Å and 2.54Å (Table 9). Two other distinct mineralogic deposits occur within this general three-part carbonate section. 1. The unconsolidated plastic mud that floors solution cavities is composed of nordstrandite, goethite, lepidocrocite, and anatase, with or without kaolinite and magnetite. Nordstrandite is a rare aluminum hydroxide mineral that has been found in Sarawak, Malaysia and Guam (Wall and others, 1962; Hathaway and Schlanger, 1965). In the Malaysia and Guam deposits, nordstrandite formed in solution cavities in limestone during subaerial weathering, probably from chemical leaching during soil formation under tropical or subtropical conditions. The other minerals in this mud also support a similar origin. The anatase is probably an alteration product of titanium-rich magnetite. 2. The brown layers and mottled sections in the carbonates consist of lepidocrocite and hematite. Because iron is the only element enriched in these brown deposits we speculate that these two iron minerals crystallized from iron oxyhydroxides that precipitated from low-temperature hydrothermal fluids produced by submarine volcanism.

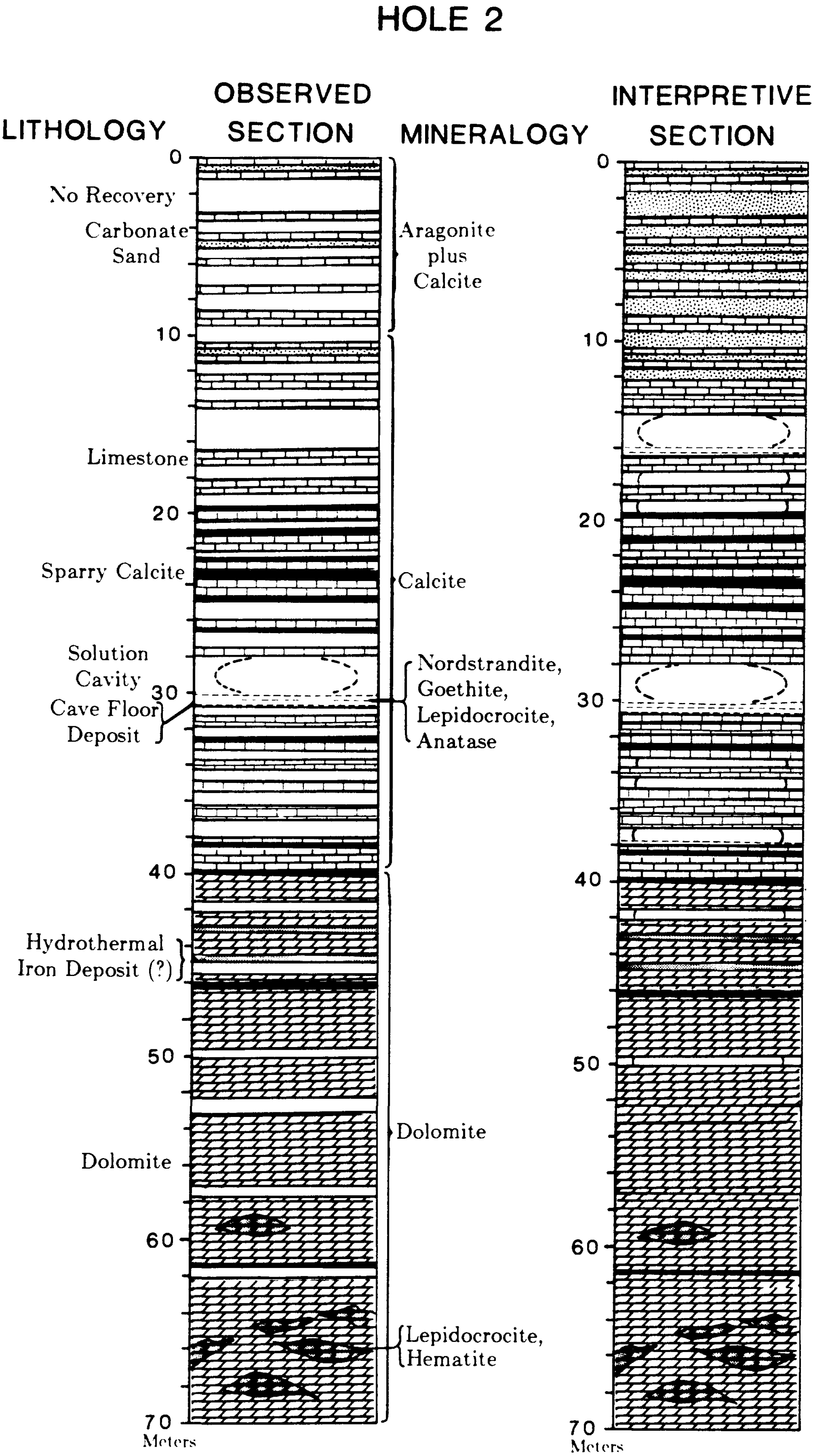

Figure 3. Stratigraphic section, general mineralogy corresponding to each lithology, and interpretive section for Hole 2.

Table 8. Mineralogy determined by x-ray diffraction for drill cores from Hole 2, Aitutaki, Cook Islands.

Sample No.[1]	Major[2]	Moderate	Minor or Trace
2-1-6	Aragonite		Calcite
2-1-32	Aragonite Calcite		
2-6-710	Aragonite		Calcite
2-7-915	Aragonite Calcite		
2-8-1053	Calcite		
2-8-1073-I	Calcite		
2-8-1073-II	Calcite		
2-10-1355	Calcite		
2-14-1926	Calcite		
2-14-1995	Calcite		
2-16-2350	Calcite		
2-16-2357	Calcite		
2-17-2433	Calcite		
2-18-2620	Calcite		
2-19-2717	Calcite		
2-20-2985	Lepidocrocite Goethite	Nordstrandite[3] Anatase	
2-21-3070	Goethite Nordstrandite	Magnetite Lepidocrocite Anatase	Kaolinite
2-23-3267	Calcite		
2-25-3529	Calcite		
2-27-3835	Calcite		Dolomite
2-29-4150	Dolomite[4]		
2-29-4155	Dolomite		
2-30-4316	Dolomite	Hematite	Lepidocrocite
2-30-4317	Dolomite		
2-32-4590	Dolomite		Calcite
2-32-4648	Calcite		
2-33-4760	Dolomite		
2-33-4809	Dolomite		Calcite?
2-33-4814	Dolomite		
2-37-5321	Dolomite		
2-37-5325	Dolomite		
2-40-5850	Dolomite		
2-41-6008A	Dolomite		
2-41-6008B	Dolomite		
2-41-6008C	Dolomite		
2-43-6179	Calcite		Dolomite
2-44-6395	Dolomite		Lepidocrocite Hematite
2-44-6432	Dolomite		
2-46-6756	Dolomite		Calcite
2-46-6758	Dolomite		Lepidocrocite Hematite?

Sample No.[1]	Major[2]	Moderate	Minor or Trace
2-47-6876	Dolomite		
2-47-6900	Dolomite		
2-47-6910	Dolomite		

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[1] First number in sample number is hole number; second number is core number; third number is distance in centimeters from top of hole (seafloor). In some cores recovery was small and the core position in the hole was arbitrarily placed, so the third number is as we wrote before. This is common for samples in Hole 6 and for four samples in Hole 5.

[2] Roughly, major is >25%, moderate is 5-25%, and minor or trace is <5% (weight percent).

[3] Formula for nordstrandite is $Al(OH)_3$.

[4] Dolomite is protodolomite with 3 to 10 mole % excess $CaCO_3$ and broad and weak ordering x-ray reflections at 2.41 Å and 2.54 Å.

Table 9. Mole percentage $MgCO_3$ in carbonates from Hole 2, Aitutaki, Cook Islands.

Sample No.	Mole % $MgCO_3$	Mineralogy	Comments
2-8-1073-I	1	Calcite	
2-8-1073-II	1	Calcite	
2-10-1355	1.5	Calcite	
2-14-1926	0	Calcite	
2-14-1995	0	Calcite	
2-16-2350	0	Calcite	
2-16-2357	0	Calcite	
2-17-2433	0	Calcite	
2-18-2620	0	Calcite	
2-19-2717	0.5	Calcite	
2-23-3267	0	Calcite	
2-25-3529	0	Calcite	
2-27-3835	0.5	Calcite	trace Dolomite
2-29-4150	42	Dolomite[1]	
2-29-4155	43	Dolomite	
2-30-4317	41	Dolomite	
2-32-4590	42	Dolomite	dolomite (major)
2-32-4590	1	Calcite	calcite (minor)
2-32-4648	1	Calcite	
2-33-4760	43	Dolomite	
2-33-4809	41	Dolomite	
2-33-4814	42	Dolomite	
2-37-5321	47	Dolomite	
2-37-5325	47	Dolomite	
2-41-6008A	41	Dolomite	
2-41-6008B	42	Dolomite	

2-41-6008C	44	Dolomite	
2-43-6179	1	Calcite	trace Dolomite
2-44-6432	41	Dolomite	
2-46-6756	40	Dolomite	
2-47-6876	41	Dolomite	
2-47-6910	42	Dolomite	

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[1] All dolomites are protodolomites as defined by excess mole percentages of $CaCO_3$ and by weak and broad x-ray reflections at 2.41 Å and 2.54 Å.

Chemical Composition

The limestones are relatively chemically pure. Magnesium and strontium were lost when aragonite converted to calcite (Table 10). Dolostones have smaller amounts of the trace elements than do the limestones, and additional elements were probably rejected when the calcite was replaced by dolomite. The mud from the floor of solution cavities is enriched in many metals, especially titanium (3.1%), chromium (0.2%), nickel (0.1%), and strontium (0.1%). The concentration of phosphorus (1.9% P_2O_5) is the second highest recorded from the Aitutaki drill cores. Perhaps the solution cavities (caves and sinkholes) were occupied by birds when the cavities formed a karst topography, and the phosphate was derived from guano. The metal enrichments suggest strong chemical leaching of volcanic rocks rich with titanium-chrome magnetite, titanaugite, and ultramafic material. The only distinguishing chemical signature of the brown beds and mottled areas is moderate to large enrichments of iron.

Table 10. Chemical composition of carbonate rocks and one mud sample from Hole 2, Aitutaki, Cook Islands.

	2-1-32	2-8-1073	2-14-1926	2-18-2620	2-25-3529	2-30-4316[1]	2-30-4317[1]
Al_2O_3	0.28	0.19	0.25	0.30	0.14	0.35	<0.1
Fe_2O_3	—	—	—	0.10	<0.04	17.5[*]	0.44[*]
FeO	0.07	0.05	0.08	0.05	<0.02	N/A	N/A
MgO	1.94	0.95	0.35	0.42	0.69	13.0	17.4
CaO	52.3	55.1	56.6	56.3	56.4	27.9	34.8
Na_2O	0.34	0.08	0.07	0.05	0.07	0.32[‡]	<0.3
K_2O	<0.02	<0.02	<0.02	<0.02	<0.02	<0.05	<0.05
TiO_2	0.02	<0.02	0.02	<0.02	0.01	<0.02	<0.02
P_2O_5	0.05	0.09	0.08	0.08	0.06	0.30	0.07
MnO[‡]	0.001	0.001	0.001	0.002	0.001	<0.02	<0.02
H_2O^-	0.21	0.02	0.05	0.06	0.02	N/A	N/A
H_2O^+	1.42	0.23	0.46	0.47	0.31	N/A	N/A
CO_2	44.2	44.5	44.9	45.2	45.0	N/A	N/A
LOI	44.3	42.9	43.6	43.5	43.8	41.07	46.80
Total[†]	99.77	101.17	101.54	101.12	101.39	101.44	99.86
Ba (ppm)	22	8	10	5	5	<20	26
Ce	<4	<4	<4	<4	<4	N/A	N/A
Co	1	2	2	2	1	20	8.8
Cr	6	7	7	10	4	140	20
Cu	2	2	3	2	2	17	9.9
La	<2	<2	<2	<2	<2	N/A	N/A
Li	<2	<2	<2	<2	<2	<50	<50
Mo	<2	<2	<2	<2	<2	N/A	N/A
Nd	4	<4	4	4	<4	N/A	N/A
Ni	3	3	5	5	3	30	9.1
Sc	<2	<2	<2	<2	<2	<10	<10
Sr	6100	760	340	300	420	230	320
V	4	<2	<2	4	<2	290	21
Zn	2	3	8	5	4	N/A	N/A
Lithology	reefal limestone	pale gray reefal limestone	reefal limestone	medium-brown reefal limestone	dense, white reefal limestone	reddish-brown hydrothermal iron hydroxide-rich dolostone	mustard yellow hydrothermal iron-hydroxide-bearing dolostone beneath 4316

	2-32-4590	2-37-5321[2]	2-44-6395	2-44-6432	2-46-6758	2-47-6910		2-21-3070
SiO_2 (wt. %)	<0.10	<0.1	0.29	0.52	0.16	1.42	SiO_2 (wt. %)	8.82
Al_2O_3	0.22	0.2	0.30	0.18	0.29	0.32	Al_2O_3	24.6
Fe_2O_3	—	0.16	3.67	—	5.58	0.10	Fe_2O_3	28.2
FeO	0.08	N/A	<0.02	0.08	0.06	0.08	FeO	0.39
MgO	18.4	19.3	19.1	18.6	18.0	18.3	MgO	3.96
CaO	35.1	32.1	31.8	34.9	31.8	34.4	CaO	1.74
Na_2O	0.13	0.12	0.12	0.15	<0.15	0.13	Na_2O	1.70
K_2O	<0.02	<0.05	<0.02	<0.02	<0.02	<0.02	K_2O	0.09
TiO_2	<0.02	0.02	0.01	0.01	<0.02	<0.02	TiO_2	5.14
P_2O_5	0.05	0.08	0.12	0.07	0.09	0.07	P_2O_5	1.89
MnO‡	0.003	0.003	0.02	0.01	0.06	0.01	MnO	0.02‡
H_2O^-	0.05	0.18	0.16	0.11	0.15	0.09	H_2O^-	3.17
H_2O^+	0.40	0.21	0.55	0.39	0.92	0.46	H_2O^+	14.5
CO_2	47.8	46.8	46.2	48.0	45.2	47.5	CO_2	2.12
LOI	46.7	47.1	45.4	46.4	44.7	45.7	LOI	22.9
Total†	100.68	99.08	100.83	100.92	100.74	100.53	Total†	99.45
Ba (ppm)	4	12	6	8	5	16	As (ppm)	190
Ce	<4	<4	<4	<4	<4	<4	Ba	67
Co	<1	1	4	1	5	5	Be	5
Cr	6	24	86	15	30	18	Cd	4
Cu	4	6	8	2	4	4	Ce	270
La	<2	4	<2	<2	<2	<2	Co	83
Li	2	2	<2	<2	<2	4	Cr	1800
Mo	<2	<2	3	<2	6	<2	Cu	63
Nd	<4	<4	<4	<4	<4	<4	Eu	7
Ni	3	5	9	3	5	12	Ga	28
Sc	<2	<2	<2	<2	<2	<2	La	170
Sr	290	130	190	250	210	260	Li	220
V	8	2	60	3	57	3	Mo	20
Zn	<2	<2	<2	<2	<2	<2	Nb	140
							Nd	120
							Ni	1300
							Pb	40
							Sc	58
							Sr	1400
							Th	33
							V	400
							Y	71
							Yb	6
							Zn	240
Lithology	dense grayish-white dolostone	dolostone	orange-brown hydrothermal iron-hydroxide-bearing dolostone	grayish-white dense dolostone	mottled brown-gray hydrothermal iron-hydroxide-bearing dolostone	dense, white dolostone with pink-white areas	Lithology	yellowish-brown pedogenic mud. Sinkhole or cave floor deposit

All analyses were performed by U.S. Geological Survey analytical laboratories in Denver, Colorado and Menlo Park, California. Ten major oxides analyzed by wavelength dispersive x-ray fluorescence spectroscopy, Denver and Menlo Park. Analytical expertise provided by J. Taggart, A. Bartel, D. Siems, R. Lerner, B. King, D. Vivit, and M. Dyslin. Some values for major elements and all minor and trace elements analyzed by inductively coupled plasma atomic emission spectroscopy, Denver. Analytical expertise provided by P. Briggs, and B. Anderson. FeO, CO_2, and water determined by wet chemical methods, Menlo Park. T. Fries, L. Espos, and S. Neil provided analytical expertise.

[1] Minor and trace elements analyzed by DC arc spectroscopy, Menlo Park. R. Lerner provided analytical expertise.

[2] The presence of organic materials prevented the accurate determination of FeO. Total Fe reported as Fe_2O_3. CO_2 value represents carbonate carbon only. See Table C in Appendix 2 for total carbon content.

— not detected.

N/A not analyzed.

* Total iron reported as Fe_2O_3.

† Totals based on LOI (loss on ignition) at 900 °C.

‡ Value reported is from emission spectroscopy data.

For the 13 carbonate samples except 2-30-4316 and 2-30-4317 the following elements were analyzed but were below detection limits (in ppm): Ag <2; As <10 except 2-44-6395 and 2-46-6758 with 50 ppm; Au <8; Be <1; Bi <10; Cd <2; Eu <2; Ga <4; Ho <4; Nb <4 (except N/A for 2-37-5321); Pb <4; Sn <10; Ta <40; Th <4; U <100; Y <2; and Yb <1. For 2-30-4316 and 2-30-4317: As <200; Be <1.0; Cd <2.0; Ga <10; Y 16 and <10 respectively.

For the one mud sample the following elements were analyzed but were below detection limits: Ag <2; Au <8; Bi <10; Ho <4; Sn <10; Ta <40; U <100.

Stable Isotopic Compositions of Calcite and Dolomite

Secondary calcite has $\delta^{13}C$ values between $-4.0^{0}/_{00}$ and $-11.0^{0}/_{00}$, averaging $-9.7^{0}/_{00}$, and $\delta^{18}O$ values between 24.6 and $26.6^{0}/_{00}$, averaging $25.3^{0}/_{00}$ (Table 11). The average $\delta^{18}O$ is less for calcite that occurs in the limestone ($25.0^{0}/_{00}$) than it is for calcite in the dolostone section ($25.7^{0}/_{00}$). This difference may be due to differences in salinity of the mineralizing waters. Analyses are from samples from 20 m to 62 m subbottom depths, and except for one $\delta^{13}C$ value, values are closely comparable. As with calcite from Hole 1, $\delta^{13}C$ values indicate derivation of the carbon from both organic matter and seawater. Formation of secondary calcite was in a dominantly freshwater environment, which is also indicated by the δD value of $-50^{0}/_{00}$ for fluid inclusions in the calcite.

The dolomite isotopic compositions are distinct from those of the calcites. $\delta^{18}O$ for dolomite averages $33.6^{0}/_{00}$ ($31.1^{0}/_{00}$ corrected for $MgCO_3$ content) and $\delta^{13}C$ averages $2.7^{0}/_{00}$ (Table 11). These values indicate that dolomite formed in a mixed seawater-freshwater environment or in a predominantly seawater environment. However, a δD of $-27^{0}/_{00}$ for the fluid inclusions in the dolomite clearly indicates a mixed seawater-freshwater environment with roughly equal amounts of each type of water. The source of the carbon was seawater.

Table 11. Carbon, oxygen, and deuterium isotopic compositions of calcite cements and dolomite from Hole 2, Aitutaki, Cook Islands.

Sample No.	$\delta^{13}C$ PDB	$\delta^{18}O$ SMOW	δD SMOW	Mineralogy	Sample Description
2-14-1995	-4.0	24.9	—	Calcite	sparry calcite layers with dog-tooth spar filled vugs
2-16-2350	-10.9	24.9	—	Calcite	up to 3-cm-long, calcite crystals
2-16-2357	-11.0	25.1	—	Calcite	same as above
2-17-2433	-10.9	25.2	—	Calcite	sparry calcite layer
2-23-3267	-10.6	24.6	—	Calcite	sparry calcite layer
2-27-3835	-10.6	25.1	—	Calcite	sparry calcite layer
2-32-4648-I	-9.1	25.3	—	Calcite	up to 2-cm-long sparry calcite crystals
2-32-4648-II	-10.1	25.2	—	Calcite	same as above
2-32-4648-III	-10.7	26.6	-50	Calcite	same as above
2-33-4760	+2.5	34.1	-27	Dolomite	dolomite
2-40-5850	+2.8	33.6	—	Dolomite	dolomite
2-43-6179	-8.8	25.8	—	Calcite	sparry calcite layer
2-47-6900	+2.9	33.2	—	Dolomite	dolomite
Average Calcite	-9.7	25.3			
Average Dolomite	+2.7	33.6			
Average Dolomite	—	31.1*			

* Corrected for mole percentage $MgCO_3$ (Tarutani and others, 1969).

Analyses performed at U.S. Geological Survey isotope laboratory by Doug White.

Uranium-Series Age Dates

Uranium content is higher than the crustal average (2.2 ppm) in the uppermost two samples (Table 12). In addition, the stratigraphically highest sample has excess ^{235}U. In nature, the α-activity of ^{235}U is about 3 to 4% of the α-activity of the ^{238}U isotope, but in near surface limestones from Aitutaki the α-activity of ^{235}U is 5 to 10% that of ^{238}U; that is a two to three times enrichment.

As with Hole 1 cores, most apparent ages are too old and probably reflect U-Th mobilization during the transformation of aragonite to calcite and calcite to dolomite, and to the presence of detrital minerals in the limestones. The age of the uppermost sample indicates a long period of nonvertical reef growth at this site, or contamination of the limestone by volcanic debris. As with the uppermost samples from Hole 1, the apparent age for sample 2-6-710 is much too old, because at 12,100 years ago global sea level was more than 20 m lower than its present level.

Table 12. Uranium and thorium contents and U-series apparent ages of coral from Hole 2, Aitutaki, Cook Islands.

Lab No.	Field No.	U ppm	Th ppm	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	U/Th age 1,000 years	Corrected age 1,000 years	Coral Types and Comments	Mineralogy (XRD)*
642	2-1-6	5.331±0.261	0.142±0.048	1.243±0.053	3.813±1.395	0.020±0.004	3.0±0.4	2.2±0.4	Excess ^{235}U; *Porites*	A(c)
884	2-6-710	3.919±0.091	0.122±0.019	1.096±0.019	12.266±1.909	0.114±0.006	13.1±0.7	12.1±0.7	*Acropora*	A(c)
643	2-10-1355	2.033±0.090	0.079±0.025	1.068±0.052	70.905±22.130	0.852±0.048	$198.5^{+47.5}_{-31.0}$	$197.2^{+46.8}_{-30.1}$	*Diploastrea*	C
644	2-14-1937	1.365±0.054	0.078±0.028	1.094±0.050	57.261±20.800	0.977±0.050	≥247	—	Recrystallized *Acropora*	C
645	2-14-1955	1.433±0.078	0.135±0.044	1.015±0.058	38.657±12.641	1.177±0.093	≥175	—	*Acropora*	C
646	2-19-2717	0.223±0.037	0.049±0.048	1.909±0.375	14.460±14.630	0.542±0.109	$78.9^{+26.5}_{-20.6}$	$75.2^{+25.5}_{-19.8}$	Recrystallized *Porites* .sp	C
647	2-29-4154	1.687±0.110	0.156±0.048	1.065±0.068	30.760±9.551	0.871±0.077	$212.0^{+111.3}_{-49.8}$	$209.0^{+105.8}_{-47.6}$	Recrystallized *Porites*	D
648	2-29-4159	1.914±6.112	0.074±0.074	1.054±0.062	81.678±81.836	0.989±0.106	≥167	—	Recrystallized *Porites* sp.	D
649	2-37-5325	1.718±0.059	0.292±0.252	1.041±0.042	22.950±19.932	1.230±0.163	≥123	—	*Porites*	D
650	2-47-6876	0.560±0.038	0.165±0.165	0.927±0.085	10.548±10.797	1.100±0.269	≥60	—	U-leaching; cemented reefal debris	D

*	Major	Moderate	Minor or Trace
Aragonite	A	(A)	(a)
Calcite	C	(C)	(c)
Dolomite	D	(D)	(d)

Petrography

Hole 2 Core 1 Depth 0.32 m
Mineralogy (XRD): Aragonite, calcite.
Classification: Coral/Algal Boundstone, Biolithite.

Two coral species occur and are encrusted by thick layers of calcareous algae (Plate 7A). Detrital micrite rich in foraminifera, echinoderms, and other small fossils infills borings and coralites. Many voids are lined with fibrous acicular aragonite rims and splays suggesting early, marine phreatic cement (Plate 7A). A few aragonite crystals altered to calcite. Abundant primary porosity results from growth-framework, intragranular pores, and syndepositional borings.

Hole 2 Core 1 Depth 0.53 m
Mineralogy (XRD): Aragonite, calcite.
Classification: Calcarenite overlying Bioclastic Wackestone, sparse Biomicrite.

Poorly cemented, poorly to moderately sorted, medium-grained calcarenite overlies a bioclastic wackestone. Clasts of *Halimeda*, red algae, gastropods, bivalves, echinoderms, coral, foraminifera, bryozoans, and pellets are coated by relatively thick micritic envelopes formed by boring endolithic algae (Plate 7B). A thin layer of equant, fine-grained microspar that precipitated as a marine phreatic void-filling cement surrounds the micritic envelopes. High intergranular porosity characterizes the calcarenite.

The wackestone is composed of relatively unaltered bioclasts of bryozoans, foraminifera, and bivalves in a detrital micrite matrix cut by a few hairline fractures. Porosity is low and predominantly moldic resulting from the preferential dissolution of bioclasts.

Hole 2 Core 8 Depth 10.73 m
Mineralogy (XRD): Calcite.
Classification: Algae- and Foraminifera-rich Packstone, Biosparite.

The packstone shows varying degrees of diagenesis and porosity. Bioclasts include abundant red algae, foraminifera (nummulites), bivalve fragments, large gastropod fragments, and worm tubes. Bryozoans, coral, echinoderms, and calcareous algae are less common. Many clasts are preserved as micritic envelopes that predominantly enclose wavy neomorphic calcite crystals or void-filling cement (Plate 8A). Some intergranular pore spaces are filled with marine phreatic, void-filling, isopachous rims and syntaxial overgrowths. Vugs cut across cement indicating that dissolution postdated cementation. Porosity varies throughout the sample but is generally high with intragranular (predominantly from worm tubes) and vuggy >> moldic.

Hole 2 Core 8 Depth 10.88 m
Mineralogy (XRD): Calcite.
Classification: Wackestone, Biosparite.

Predominant bioclasts include benthic foraminifera (miliolids, nummulites, and others) and coral fragments with fewer red algae and echinoderms. Bioclasts vary in degree of preservation. Grains are supported in a detrital micrite matrix and calcite cement. Although isopachous cement rims occur, the majority of the cement is neomorphic calcite. Localized recrystallization of primary void-filling cements occurred within some molds. A complex history of diagenetic events including deposition, void-filling cementation (Plate 8B), neomorphism, dissolution, further void-filling cementation (marine?), and further dissolution is evident. Some large, channel-like vugs are present. The high porosity in this sample results from abundant secondary vugs and molds.

Hole 2 Core 14 Depth 19.26 m
Mineralogy (XRD): Calcite.
Classification: Coral Boundstone and Packstone, Coral Biolithite, Packed Biomicrite.

Two components occur: 1) recrystallized coral encrusted by large curving laminar algal mats, and 2) poorly sorted packstone containing bioclasts of foraminifera, red algae, echinoderms, gastropods, and bryozoans. The primary aragonite coral crystals inverted to fine-grained calcite crystals. Micritic envelopes that outline coral pores are infilled with both void-filling and neomorphic calcite (Plate 9A). Neomorphic calcite may have originated from the secondary recrystallization of the void-filling cement. Bioclasts within the packstone are preserved as micritic envelopes outlining molds, void-filling cement, and neomorphically derived spar. At least two generations of cementation are evident within some larger vugs. Pore walls are lined by isopachous rims of fine-grained subhedral and, in some places, slightly acicular aragonite crystals (recrystallized marine phreatic void-filling cement) followed by larger euhedral, somewhat elongate calcite crystals of freshwater origin. In some pores, formation of these elongate crystals was followed by formation of smaller equant void-filling calcite crystals (freshwater origin). It is evident from the presence of smaller molds that a period of dissolution postdated void-filling. Porosity, though variable, is on the average, moderate with moldic > vuggy.

Hole 2 Core 16 Depth 22.99 m
Mineralogy (XRD): Calcite.
Classification: Coral Boundstone, Coral Biolithite.

Large, bulbous algal laminae, recrystallized coral, and bioclasts of echinoderms, gastropods, and foraminifera comprise this sample. Although some bioclasts are infilled by void-filling cement, the majority are neomorphic calcite. Large channels are infilled by a typical sequence of void-filling calcite: a thin layer of subhedral crystals; larger, somewhat elongate crystals; and very large, equant euhedral crystals typical of freshwater phreatic cement. Some of these void-filling crystals neomorphosed further to calcite with wavy, diffuse contacts. A thin layer of copper-colored organic material coats many void surfaces. Geopetal fabrics are present within molds and borings due to the deposition of micrite into the primary pore spaces. Small dissolution vugs that crosscut primary cement are coated with a thin isopachous calcite rim and attest to a later dissolution/void-filling event. This sample has moderate porosity with channel > vuggy.

Hole 2 Core 18 Depth 26.28 m
Mineralogy (XRD): Calcite.
Classification: Wackestone, Pelmicrite.

Fine-grained micrite with copper-colored pellets (oxidized iron-rich volcanic ash mixed with fine mud?) contains ghosts and casts of ostracodes and foraminifera. Pale areas within the micrite may represent burrows. Large elongate and equant euhedral sparry calcite crystals of freshwater phreatic origin fill channels. These void-filling crystals commonly trap sparse detrital micrite and volcanic ash between crystals, which were deposited while the crystals were growing. Porosity is moderate to low and produced by small molds and a few larger dissolution vugs.

Hole 2 Core 25 Depth 35.40 m
Mineralogy (XRD): Calcite.
Classification: Recrystallized Boundstone and Mudstone, Coral Biolithite and Micrite.

This sample includes recrystallized coral (Plate 9B) encrusted by algal layers; fine-grained, graded micrite with small copper-colored pellets (originating from organic matter or oxidized iron minerals); and red algae and foraminifera casts in a micrite matrix. A thin isopachous rim of marine phreatic, subelongate, subhedral calcite crystals lines fracture voids and fossil molds. The fracture voids are further filled by large freshwater void-filling calcite crystals. Some neomorphism of these void-filling crystals is evident. Lithophagous borings in which recrystallized detrital micrite underlies void-filling cement show geopetal fabric. Porosity varies throughout the sample but is moderate and predominantly moldic.

Hole 2 Core 29 Depth 41.60 m
Mineralogy (XRD): Dolomite.
Classification: Dolomite Boundstone, Dolomite Biolithite.

Recrystallized, dolomitized coral occurs with thick sheets of moderately preserved algae and pockets of dolomitized bioclasts in a detrital matrix. Bioclasts include red algae, foraminifera, echinoderm plates, and bryozoans. Some worm or bivalve tubes are partly filled with detrital micrite with a geopetal fabric; the unfilled part of the boring is lined by dolomitized isopachous cement rims. Pervasive dolomitization may have obliterated evidence of earlier cementation. All void spaces are bounded by a thin rim of dolomite rhombs that may have crystallized over a previous void-filling phreatic calcite cement rim. Porosity is moderate and vuggy. Some vugs are occluded with micritic geopetal infill that was subsequently dolomitized, indicating that detrital deposition postdates vug formation.

Hole 2 Core 30 Depth 43.2 m
Mineralogy (XRD): Dolomite.
Classification: Dolomitized Coral Boundstone, Dolomitized Biolithite.

Two species of coral are encrusted with thick algal laminae; all fossils are dolomitized. Layers of algal laminae are interbedded with lenses of laminated, fine-grained dolomite with some rust-colored stains (oxidized iron minerals). Porosity is moderate to low and dominantly vuggy.

Hole 2 Core 32 Depth 46.00 m
Mineralogy (XRD): Dolomite; minor calcite.
Classification: Dolomitized Boundstone, Dolomitized Biolithite.

Four distinct textures occur: 1) dolomitized coral, 2) thick laminated layers of dolomitized encrusting algae, 3) medium-large fossil molds in a medium-grained crystalline dolomite matrix, and 4) crystalline dolomite that coarsens upward and contains abundant small fossil molds. Thin layers of dolomitized isopachous cement line bioclast molds. One large void-filling calcite crystal may represent late-stage freshwater cementation. Overall, this sample has high porosity with moldic porosity in the crystalline dolomite and vuggy and framework porosity in the dolomitized coral.

Hole 2 Core 33 Depth 48.12 m
Mineralogy (XRD): Dolomite.
Classification: Algal Boundstone/Biolithite and Crystalline Dolomite.

Two distinct textures occur. An algal boundstone, extensively bored, contains large, spherical laminated red algae and casts of bivalves, gastropods, worm tubes, and foraminifera. All fossils are dolomitized. The worm tubes are partly or completely infilled with fine-grained detrital micrite (Plate 11A). The overlying medium-grained crystalline dolomite truncates the boundstone with a sharp contact. Pervasive dolomitization obscures much of the original structure, but red algae, mollusks, and echinoderm clasts are identifiable (Plate 10A). Some clasts show remnant void-filling and neomorphic cements that were subsequently dolomitized (Plate 10B) while other clasts are surrounded by two layers of fine-grained micrite. Fine-grained, isopachous cement rims that are infilled with large equant freshwater phreatic calcite crystals and dolomite crystals (Plate 10B) indicate the following cementation sequence: deposition, dissolution, freshwater void-filling cementation, and dolomitization. Geopetal structures are abundant. Porosity is moderate to high and varies throughout the sample with vuggy > moldic.

Hole 2 Core 37 Depth 53.21 m
Mineralogy (XRD): Dolomite.
Classification: Recrystallized Coral Boundstone/Biolithite and Crystalline Dolomite.

Moderately well-preserved dolomitized coral (*Goniopora*) and crystalline dolomite probably crystallized from an originally detrital micritic matrix. In addition to boring structures, fossil molds of mostly unrecognizable precursor fossils occur. A few gastropod, sponge spicule, red algae clasts, and laminar algal mats were identified. Detrital micrite filled coral pore spaces leaving spherical detrital casts. Evidence for early calcite cementation has been largely obliterated by dolomitization and extensive dissolution. However, a very thin dolomitized void-filling cement layer is evident in some large vugs. The discontinuous appearance of many of these rims may be due to partial dissolution. Abundant molds and large dissolution vugs give this sample very high porosity.

Hole 2 Core 41 Depth 60.08 m
Mineralogy (XRD): Dolomite.
Classification: Dolomite Grainstone.

Two distinct textures occur: 1) crystalline dolomite containing abundant casts of bivalves, branching red algae, foraminifera (nummulites), worm tubes (Plate 11B), encrusting algae, possible bryozoans, and borings; and 2) laminated fine-grained dolomitized micrite and iron-stained dolomitized micrite suggesting several episodes of deposition. A large shell bed with well-preserved gastropods and borings is distinctive. Excellent geopetal fabric formed and several modes of cement development are apparent. Many shell walls were neomorphosed. Fine-grained dolomite, which probably recrystallized from detrital mud as indicated by its geopetal fabric, partly or completely fills pores and shell chambers. Phreatic void-filling calcite spar was also dolomitized. High porosity occurs that is dominantly moldic with a few dissolution vugs.

Hole 2 Core 44 Depth 63.96 m
Mineralogy (XRD): Dolomite; minor lepidocrocite, hematite.
Classification: Crystalline Dolomite.

Two fine-grained crystalline dolomite textures are present (Plate 12A). One dolomite is stained rust-orange by iron hydroxides and shows a sharp contact with iron-free dolomite. Both textures contain abundant molds, ghosts of pellets, bivalve casts, ostracodes, and foraminifera (Plate 12B). Well-preserved red calcareous algae clasts (Plate 13A) are concentrated in two laminae. Dolomite crystals of various sizes show layering and grading that may reflect primary depositional fabric. Dolomitization obliterated most evidence of early cementation. Unstained dolomite crystals filling molds in the iron-stained dolomite attest to a later period of iron-free, void-filling cementation. One pore contains large, partially dissolved calcite crystals that formed in a freshwater phreatic environment. Porosity is moderate to high. Small molds and intercrystalline microvoids are common throughout both textures. Overall porosity is high with moldic>> vuggy > intercrystalline.

Hole 2 Core 46 Depth 67.56 m
Mineralogy (XRD): Dolomite; minor calcite.
Classification: Crystalline Dolomite and Laminated Fe-stained Dolomite.

Three dolomitized coral units (Plate 13B) are separated by fractures: 1) finely crystalline, rust-colored, iron-stained dolomite overlies dolomitized pellets; 2) laminated unstained and stained dolomite contains one lamina of dolomitized bioclasts, and 3) unlaminated, unstained dolomite contains abundant clasts of red algae and some ostracodes(?). Unit 3 contains large elongate voids (borings?) that are partly infilled with dolomitized micrite displaying geopetal fabric. Molds within this unit are rimmed with large dolomite rhombs that replaced previous void-filling cement. Similar rims within units 1 and 2 are finer-grained and, in places, discontinuous. The presence of large, equant, crystals filling fracture voids indicates that an episode of freshwater phreatic cementation postdated dolomitization. Many of these equant crystals are partly dissolved. Porosity is moderate with moldic > fracture > intercrystal and intraparticle.

Hole 2 Core 47 Depth 69.10 m
Mineralogy (XRD): Dolomite.
Classification: Dolomite Boundstone, Dolomitized Biolithite.

Strings of dolomite crystals represent remnants of coral. The coral is bounded by fine-grained dense dolomite that may have replaced encrusting algal laminae. Abundant, well-preserved branching red algal clasts, some ostracodes, borings, and abundant molds occur in a medium-grained dolomite matrix. Dolomitized, void-filling cement rims some molds. Several well-developed cement rims occur within large, elongate voids that are bounded by a dark micritic ring. These complex cement rims result from interparticle cementation followed by dissolution of the bioclast and further void-filling cementation within the mold (Plate 14A). Overall porosity is very high but varies through the sample with moldic > intragranular > vuggy.

Summary of Hole 2

Hole 2 is the deepest one drilled and consists predominantly of carbonate deposits. The predominance of coral at all depths (Table 13) suggests a relatively high-energy reef environment, consistent with the present location of the site close to the reef flat. Algae, foraminifera, and mollusks are present throughout and do not show systematic variation with depth. Changes in porosity and cementation with depth roughly correspond to mineralogical changes and define three diagenetic zones or stratigraphic intervals.

Zone 1, 0 to 10 m, is composed of primary skeletal aragonite and some calcite. Minor aragonite and calcite void-filling cement is of marine phreatic origin. High porosity is the result of primary growth framework and intra- and intergranular porosity. The aragonite is rich in strontium and magnesium and lithologies are limestone interbedded with carbonate sand.

Zone 2, 10 to 40 m, is composed of secondary calcite. Bioclasts were neomorphosed and void-filling cement is common. In places, marine phreatic cement is overprinted with freshwater phreatic cement. Secondary porosity from the dissolution of grains and cements gives moderate to high moldic and vuggy porosity. Oxygen and carbon isotopic compositions on sparry calcite cements indicate formation in predominantly freshwater, but with some fluctuation in salinity. Organic matter and seawater were the sources of carbon. Sr and Mg were lost as aragonite was replaced by calcite. Large solution cavities that occur in this stratigraphic interval formed during subaerial and subsurface karst development, and intense chemical leaching, which deposited mud rich in the metals titanium, chromium, and nickel and in the elements phosphorus and strontium on the floors of the cavities.

Zone 3, 40 to 69 m, is composed of secondary dolomite. Dolomitization is pervasive and masks or partially masks primary grains and several stages of cementation. Dolomitized freshwater void-filling cements are noted. Toward the bottom of the section, minor freshwater phreatic cementation succeeded dolomitization. Porosity is high and predominantly vuggy and moldic, with intercrystalline porosity more important in the lowermost 5 m of the section. The high porosity facilitated good flush-water flow. Oxygen and carbon isotopic compositions of calcite cements indicate the same conditions of formation as in the overlying limestone section, although the salinity of the mineralizing fluids may have been somewhat higher. The isotopic composition of the dolomite, however, is much different and indicates formation under mixed freshwater and seawater conditions, with roughly equal amounts of each forming a mixing zone where dolomite replaced calcite. The carbon and the magnesium were derived from seawater. Nearby volcanic hydrothermal activity was recorded in zone 3 as layers and mottled zones enriched with iron.

Table 13. Summary of petrography, Hole 2.

Geology

Depth (m)	Mineralogy	Major Diagenetic Fabrics	Minor Diagenetic Fabrics	Major Porosity Types	Minor Porosity Types	Degree of Porosity
0.32	A,C	AA	—	GF	I	A
0.53	A,C	VF/mp	—	i	M	A
10.73	C	VF/mp	N	V,I	M	A
10.88	C	N	VF/mp	M,V	—	A
19.26	C	N	VF/fp,mp	M	V	M
22.99	C	N	VF/fp,mp	C	V	M
26.28	C	VF/fp	—	M	V	M-m
35.40	C	VF/fp,mp	N	M	—	M
41.60	D	D	VF	V	—	M
43.2	D	D	—	V	—	M-m
46.00	D>>C	D	VF/fp	M	V	A
48.12	D	D	N,VF/fp	V	M	M-A
53.21	D	D	VF	M	V	A
60.08	D	D	N,VF	M	V	A
63.96	D>>I	D	VF/fp	M	V,X	A-M
67.56	D>>C	D	VF/fp	M	F,X,I	M
69.10	D	D	VF	M	I,V	A

Biology

Depth (m)	Coral	Algae	Mollusks	Echinoderms	Bryozoa	Foraminifera	Sponges	Worm Tubes
0.32	*	*	—	X	—	X	—	—
0.53	*	*	*	*	*	*	—	—
10.73	X	*	*	X	X	*	—	X
10.88	*	X	—	X	—	*	—	—
19.26	*	*	*	*	*	*	—	—
22.99	*	*	*	*	—	*	—	—
26.28	—	—	—	—	—	*	—	—
35.40	*	*	—	—	—	*	—	—
41.60	*	*	—	X	X	X	—	X
43.2	*	*	—	—	—	—	—	—
46.00	*	*	—	—	—	—	—	—
48.12	—	*	*	X	—	X	—	X
53.21	X	X	X	—	—	—	X	—
60.08	—	*	*	—	*	*	—	—
63.96	—	*	*	—	—	*	—	—
67.56	—	*	*	—	—	—	—	—
69.10	X	*	X	—	—	—	—	—

Key to Table 13

Mineralogy:
C: Calcite
A: Aragonite
D: Dolomite
I: Iron Minerals

Cements: Type/Origin

Type:
VF: void-filling sparry calcite
N: neomorphically derived sparry calcite
AA: aragonitic
D: dolomitization

Origin:
mp: marine phreatic
fp: freshwater phreatic

Porosity: Degree/Development

Development:
M: moldic
GF: growth framework
V: vuggy
I: intraparticle
i: interparticle
C: channel
X: intercrystal
F: fracture

Degree:
Abundant porosity: A
Moderate porosity: M
Minor porosity: m

Biota:
* abundant
X present
— absent

HOLE 3

Hole 3 is located adjacent to the fringing reef of Aitutaki Island (Fig. 1). The drill string was spudded into a low-lying bench of a coral knoll adjoining a carbonate sand-filled depression. Seismic-reflection profiles show a prominent subbottom acoustic reflector that forms peaks and valleys with a relief of about 20 m. The water depth is 3 m.

Lithology

About 1 m of framework coral limestone was recovered from the coral head (Fig. 4). The limestone overlies 9 m of carbonate sand mixed with minor amounts of basaltic debris. Little of this sand was recovered because most washed out the drill pipe. From 10 m to 11 m subbottom depth is a framework coral limestone bed capped by a thin layer of bioclastic limestone. From about 11 m to 15 m is greenish-brown volcaniclastic mud and silt mixed with pebbles of reefal limestone. From 15 m to 30 m is sticky greenish-brown mud that contains sand and silt grains in the upper 2 m. One thin (1.5 cm) hard black mud was recovered from this section. From 30 m to 33 m is brown silty mud which is probably altered pyroclastic or volcanic debris. All these muds are pedogenic. From 33 m to 37 m is interbedded silty mud and alkalic basalt flows. From 37 m to 40 m are alkali olivine basalt flows containing patches and filled vesicles of calcite (Plate 3A). Red mud coating the cores may be interbedded with the basalt flows or may be a paleosol. The basalts were probably erupted in a marine environment.

Mineralogy

The carbonate sand and limestone section extends to about 11 m subbottom depth. Aragonite is the predominant carbonate mineral from 0 m to 8 m and calcite from 8 m to 11 m (Table 14). Limestone pebbles in the greenish-brown mud are also calcite and occur to 14 m depth. The 22-m thick greenish-brown mud section is composed primarily of kaolinite, goethite, and magnetite. Nordstrandite, lepidocrocite, and possibly hematite are present in parts of this mud section. These minerals were produced by moderate to intense chemical leaching of volcanic and pyroclastic rocks in a subaerial environment. With the exception of magnetite, all primary volcanic minerals such as olivine, plagioclase, and pyroxene as well as glass were completely altered. The alkalic basalt is composed of primary olivine, pyroxene, plagioclase, and magnetite, and secondary smectite. Vesicles and vugs are filled with white to green calcite or dull-green smectite. The mud interbedded with the upper basalt flows contains the same primary volcanic minerals and alteration products. The red mud interbedded(?) with the lower basalt flows is composed of the same minerals, but with more smectite and some calcite. This mineral suite suggests moderate chemical weathering of the alkalic basalts.

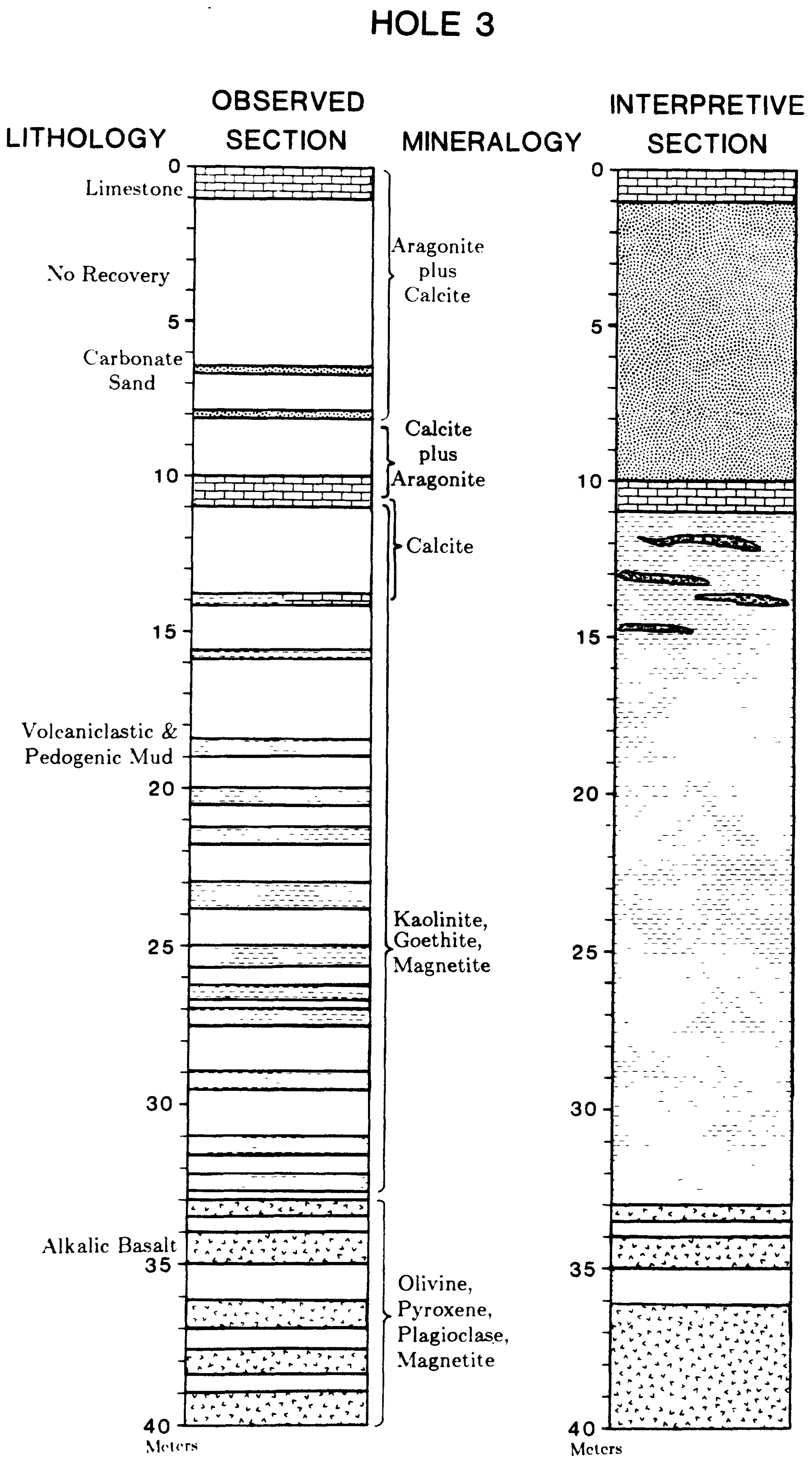

Figure 4. Stratigraphic section, general mineralogy corresponding to each lithology, and interpretive section for Hole 3.

Table 14. Mineralogy determined by x-ray diffraction for drill cores from Hole 3, Aitutaki, Cook Islands.

Sample No.[1]	Major[2]	Moderate	Minor or Trace
3-1-7	Aragonite		
3-1-50	Aragonite		
3-1-72-I	Aragonite Calcite		
3-1-72-II	Aragonite	Calcite	
3-1-72-III	Aragonite		Calcite
3-4A-650	Aragonite	Calcite	
3-5A-799	Aragonite	Calcite	
3-7-1070	Calcite		Aragonite
3-7-1075	Calcite		
3-9A-1420	Calcite	Goethite Kaolinite Magnetite	Nordstrandite[3] Anatase Hematite?
3-10A-1585	Goethite	Kaolinite Nordstrandite Anatase	Lepidocrocite Magnetite Hematite
3-12A-1865	Goethite Kaolinite Magnetite	Anatase	Nordstrandite
3-13A-2015	Kaolinite Magnetite Goethite	Anatase	Nordstrandite Analcime?
3-16A-2472	Kaolinite Magnetite Goethite	Anatase	
3-19A-2922	Kaolinite Goethite Magnetite	Anatase	
3-20A-3073	Kaolinite Goethite Magnetite		Anatase
3-23-3469	Pyroxene Plagioclase	Smectite Olivine	
3-24A-3690	Goethite Magnetite Pyroxene	Plagioclase K-feldspar Smectite	Mixed layer clay minerals? Apatite?
3-24A-3693	Pyroxene	Magnetite Celadonite K-feldspar Goethite Smectite	Apatite
3-25-3741	Pyroxene	Plagioclase K-feldspar Olivine	Smectite Apatite?
3-25-3778	Pyroxene	Plagioclase K-feldspar Olivine	Smectite Apatite?

Sample No.[1]	Major[2]	Moderate	Minor or Trace
3-25-3787	Smectite		
3-26-3872	Calcite		
3-26-3887	Pyroxene	K-feldspar Plagioclase Olivine	Smectite Kaolinite Amphibole
3-26-3893	Calcite		Smectite Celadonite Amphibole
3-26-3938	Goethite Smectite Pyroxene Magnetite	Plagioclase	Calcite Hematite Mixed layer clay minerals? Apatite?

[1] First number in sample number is hole number; second number is core number; third number is distance in centimeters from top of hole (seafloor). In some cores recovery was small and the core position in the hole was arbitrarily placed, so the third number is as we wrote before. This is common for samples in Hole 6 and for four samples in Hole 5.

[2] Roughly, major is >25%, moderate is 5-25%, and minor or trace is <5% (weight percent).

[3] Formula for nordstrandite is $Al(OH)_3$.

Chemical Composition

The aragonite limestone is pure and is high in strontium. The calcite limestone is also pure and shows a loss of strontium and a little contamination by volcanic detritus indicated by a relatively higher aluminum content (Table 15). The greenish-brown mud and brown mud are oxidized iron-rich deposits that have high concentrations of titanium, phosphorus, barium, chromium, nickel, thorium, and strontium, and, in places, high concentrations of manganese, arsenic, cobalt, lithium, and uranium (Tables 15, 16). The highest concentrations of phosphate (nearly 3% P_2O_5) from the Aitutaki drill cores are found in these muds. Iron decreases with depth in the mud section and chromium and titanium show a similar but less well-developed trend. By comparing the chemical composition of the muds with the basalts (Table 15) it is clear that chemical leaching of the basalts and soil formation under tropical to subtropical conditions removes silicon, magnesium, calcium, sodium, potassium, and concentrates aluminum, iron, titanium, phosphorus, arsenic, chromium, lithium, nickel, and other refractory elements. The oxidized iron indicates weathering of the basalts in an oxidizing environment. Although the basalts were probably erupted in a submarine environment, they were weathered and altered in a subaerial environment.

Table 15. Chemical composition of reefal limestones (columns 1-2), and volcanogenic rocks and sediments (columns 3-8) from Hole 3, Aitutaki, Cook Islands.

	3-1-50	3-7-1075		3-10A-1585	3-13A-2015	3-16A-2472	3-20A-3073	3-23-3469	3-26-3887
SiO_2 (wt. %)	0.63	0.90	SiO_2 (wt. %)	17.3	22.4	27.4	28.3	44.8	44.3
Al_2O_3	0.10	0.82	Al_2O_3	23.8	23.1	21.1	24.3	11.6	11.7
Fe_2O_3	—	0.53	Fe_2O_3	31.1	25.7	22.6	18.4	3.06	3.86
FeO	0.09	0.22	FeO	0.40	<0.02	0.31	0.27	8.23	6.97
MgO	0.41	0.59	MgO	1.00	0.70	1.01	0.58	12.1	12.5
CaO	53.4	54.8	CaO	0.43	0.38	0.54	1.05	10.4	11.1
Na_2O	0.53	<0.15	Na_2O	1.02	1.22	1.80	1.16	3.22	2.90
K_2O	<0.02	<0.02	K_2O	0.11	0.13	0.25	0.13	1.11	1.10
TiO_2	<0.02	0.11	TiO_2	4.76	4.29	4.67	3.97	1.83	1.85
P_2O_5	<0.05	0.11	P_2O_5	1.38	1.20	1.18	2.77	0.89	0.83
MnO	0.001‡	0.01‡	MnO	0.08	2.71	0.39	0.11	0.17	0.16
H_2O^-	0.31	0.16	H_2O^-	3.10	3.64	6.06	4.15	0.82	1.13
H_2O^+	1.80	0.49	H_2O^+	13.0	10.2	8.76	12.3	1.46	1.62
CO_2	43.3	43.3	CO_2	0.81	0.47	0.25	0.42	0.32	0.32
LOI	44.6	42.8	LOI	18.9	18.1	18.5	17.6	1.97	2.64
Total†	99.76	100.89	Total†	100.28	99.93	99.75	98.64	99.38	99.91
Ba (ppm)	9	18	As (ppm)	210	90	30	30	<10	<10
Ce	<4	7	Ba	410	1200	790	1900	660	880
Co	1	4	Be	5	4	4	4	1	1
Cr	1	52	Cd	3	2	2	<2	3	2
Cu	<1	4	Ce	250	220	350	390	120	110
La	<2	<2	Co	140	610	72	59	61	60
Li	<2	3	Cr	1400	1200	820	1000	580	610
Mo	<2	<2	Cu	69	150	66	42	43	48
Nd	<4	5	Eu	8	7	10	13	4	4
Ni	<2	20	Ga	34	54	36	36	21	20
Sc	<2	<2	La	140	140	210	240	69	66
Sr	7200	1100	Li	160	250	64	69	12	11
V	<2	11	Mo	11	6	<2	2	<2	<2
Zn	7	9	Nb	100	100	130	81	38	38
			Nd	120	100	160	190	56	54
			Ni	970	1200	530	690	360	320
			Pb	23	18	26	24	12	10
			Sc	49	47	40	38	19	20
			Sr	1400	1100	860	7100	1100	1000
			Th	26	31	39	25	10	11
			V	370	380	230	240	140	150
			Y	84	74	75	100	28	28
			Yb	6	5	6	5	2	2
			Zn	250	220	220	230	110	110
Lithology	white, reefal limestone	black reefal limestone fragments	Lithology	brown, slightly sandy pedogenic mud	brown and black slightly silty pedogenic mud	brown pedogenic mud	sandy brown pedogenic mud with goethite streaks	coarse-grained alkalic basalt	medium-grained alkalic basalt

All analyses were performed by U.S. Geological Survey analytical laboratories in Denver, Colorado and Menlo Park, California. Ten major oxides analyzed by wavelength dispersive x-ray fluorescence spectroscopy, Denver and Menlo Park. Analytical expertise provided by J. Taggart, A. Bartel, D. Siems, R. Lerner, B. King, D. Vivit, and M. Dyslin. Minor and trace elements analyzed by inductively coupled plasma atomic emission spectroscopy, Denver. Analytical expertise provided by P. Briggs, and B. Anderson. FeO, CO_2, and water determined by wet chemical methods, Menlo Park. T. Fries, L. Espos, and S. Neil provided analytical expertise.

— not detected.

† Totals based on LOI (loss on ignition) at 900 °C.

‡ Value reported is from emission spectroscopy data.

For the two carbonate samples the following elements were analyzed but were below detection limits (in ppm): Ag <2; As <10; Au <8; Be <1; Bi <10; Cd <2; Eu <2; Ga <4; Ho <4; Nb <4; Pb <4; Sn <10; Ta <40; Th <4; U <100; Y <2; and Yb <1.

For the six volcanic and mud samples the following elements were analyzed but were below detection limits: Ag <2; Au <8; Bi <10; Ho <4; Sn <10; Ta <40; U <100.

Uranium-Series Age Dates

Uranium and thorium contents of the mud are very high, 13 ppm and 49 ppm, respectively (Table 16). In the limestones, uranium is higher and thorium is lower than they are in average limestone (Turekian and Wedepohl, 1961). Excess ^{235}U was measured in the limestone samples.

The age of the mud at 14 m depth is >88,100 years and reflects the age of basaltic material, or its alteration products, and uranium leaching. The apparent age of the limestone at 10.7 m (62,000 years) may also have been influenced by diagenesis as aragonite altered to calcite.

Table 16. Uranium and thorium contents and U-series apparent ages of coral from Hole 3, Aitutaki, Cook Islands.

Lab No.	Field No.	U ppm	Th ppm	$\frac{^{234}U}{^{238}U}$	$\frac{^{230}Th}{^{232}Th}$	$\frac{^{230}Th}{^{234}U}$	U/Th age 1,000 years	Corrected age 1,000 years	Coral Types and Comments	Mineralogy (XRD)*
651	3-1-16	2.884±0.097	—	1.143±0.036	—	—	Recent	—	Excess ^{235}U; *Porites*	A
652	3-7-1070	4.657±0.149	0.448±0.087	1.200±0.034	17.223±3.344	0.454±0.028	$64.3^{+5.7}_{-5.3}$	$61.5^{+5.5}_{-5.1}$	Excess ^{235}U; *Pocillopora*	C(a)
653	3-9A-1420	12.942±1.044	48.832±5.318	1.129±0.118	1.960±0.241	2.152±0.229	>88	—	Volcaniclastic mud	—

*	Major	Moderate	Minor or Trace
Aragonite	A	(A)	(a)
Calcite	C	(C)	(c)

Petrography

Hole 3 Core 1 Depth 0.07 m
Mineralogy (XRD): Aragonite.
Classification: Coral Boundstone, Biolithite.

Unaltered coral contains minute borings. Pores are predominantly empty except for rare micritized peloids and cement linings that suggest cementation within the marine phreatic zone. Porosity is high and of the growth-framework type.

Hole 3 Core 1 Depth 0.72 m
Mineralogy (XRD): Aragonite, calcite.
Classification: Coral and Algal Boundstone, Biolithite.

A complex sequence of events is preserved in this sample starting with the growth of coral over a shell fragment. Preservation of small borings within the original coral wall indicates that the coral is unaltered. The pores are partly filled by clastic micrite. Vugs were created either by boring organisms or by dissolution. The coral is covered by two layers of massive calcareous red algae. Both layers of red algae contain several large- and medium-sized borings that were partly or completely filled by clastic micrite. Acicular isopachous aragonite cement lines many of the coral pores but is absent from the voids created by borings and dissolution. Porosity is moderate with growth-framework > vuggy.

Hole 3 Core 7 Depth 10.8 m

Mineralogy (XRD): Calcite.
Classification: Coral Boundstone to Skeletal Grainstone, Biolithite.

Coral (Plate 15A) is capped by a layer of medium- to fine-grained grainstone (Plate 15B) containing benthic foraminifera, mollusks, bryozoa, calcareous red algae, *Halimeda* plates, and phenocryst minerals from volcanic rocks (Plates 15A,B, 16A). The original aragonitic coral neomorphosed to a mosaic of calcite crystals (Plate 15A). The majority of coral pores were filled with void-filling sparry calcite and several fragments within the calcarenite underwent inversion or were dissolved and filled by void-filling freshwater phreatic sparry calcite. Porosity is moderate with growth-framework > moldic > vuggy.

Hole 3 Core 9A Depth 14.20 m
Mineralogy (XRD): Major calcite; moderate goethite, kaolinite, magnetite; trace nordstrandite, anatase.
Classification: *Halimeda* Packstone, poorly washed Biosparite.

Halimeda plates are the predominant bioclast (Plate 16B). A few fragments of calcareous red algae and benthic and pelagic foraminifera are also present. Micrite and void-filling sparry calcite surround the grains. The micrite is stained a pale to medium brown due to iron-bearing minerals. Individual crystals of weathered mafic minerals, like those in nearby basalt outcrops, are present in the micrite. The *Halimeda* plates neomorphosed to microspar and retain faint wall structure (Plate 16B). Porosity is moderate and intraparticle.

Hole 3 Core 23 Depth 34.69 m
Mineralogy (XRD): Major pyroxene, plagioclase; moderate smectite, olivine.
Classification: Alkali Olivine Basalt.

Altered aphanitic basalt consists of small plagioclase and titanaugite crystals and olivine phenocrysts. Altered glass or dissolution voids were filled by clay minerals and hydrous iron oxides. Vesicles were filled by void-filling calcite. The basalt probably erupted in a submarine environment.

Hole 3 Core 24A Depth 36.93 m
Mineralogy (XRD): Major pyroxene; moderate magnetite, celadonite, K-feldspar, goethite, smectite; trace apatite.
Classification: Alkalic Basalt.

Moderately altered basalt contains olivine phenocrysts that altered to goethite. Voids created by the dissolution of glass were infilled by clay minerals and possibly zeolites. Crystals of plagioclase are almost completely replaced by clay minerals whereas pyroxene is fresh.

Hole 3 Core 25 Depth 37.41 m
Mineralogy (XRD): Major pyroxene; moderate plagioclase, K-feldspar, olivine; trace smectite.
Classification: Alkalic Basalt.

Relatively unaltered basalt shows minor replacement of unstable minerals and glass by clay minerals and zeolites.

Hole 3 Core 26 Depth 38.87 m
Mineralogy (XRD): Major pyroxene; moderate K-feldspar, plagioclase, olivine; minor smectite,

chlorite, amphibole.
Classification: Alkalic Basalt.

This basalt is relatively unaltered with minor replacement of unstable minerals and glass by clay minerals and zeolites.

Summary of Hole 3

Starting from the lagoon floor, Hole 3 consists of 11 m of limestone and carbonate sand, 4 m of mixed limestone and mud, 18 m of volcanogenic and pedogenic mud, 4 m of interbedded mud and basalt flows, and 3 m of basalt. In the limestone, coral and algae are the predominant bioclasts with bryozoa, mollusks, and foraminifera also present (Table 17). Aragonite changes to calcite at 8 m subbottom and the diagenetic fabric changes from acicular aragonite cementation above to freshwater phreatic void-filling cementation and minor to moderate neomorphism below. Porosity also shifts from a primary growth framework type to secondary dissolution vugs and molds.

The mud was produced by moderate to intense chemical leaching of basaltic volcanic rocks, which eliminated primary minerals except magnetite and produced predominantly kaolinite and goethite. This leaching occurred in a subaerial environment and concentrated many metals including most importantly aluminum, iron, titanium, chromium, nickel, uranium, and thorium. The very low permeability of these sticky muds inhibited the through-flow of fluids which facilitated maintenance of variable concentrations of metals at different stratigraphic levels. The muds formed as soils from tropical to subtropical weathering of the basalts. The basalt is an alkali olivine basalt that erupted in a marine environment.

Table 17. Summary of petrography, Hole 3.

Geology

Depth (m)	Mineralogy	Major Diagenetic Fabrics	Minor Diagenetic Fabrics	Major Porosity Types	Minor Porosity Types	Degree of Porosity
0.07	A	AA	VF	GF	—	A
0.72	A,C	AA	VF	GF	V	M
10.8	C>>A	N	VF/fp	GF	M,V	M
14.2	C>>I,K	N	VF	I	—	M
34.69	S>K	—	VF	—	—	—
36.93	S>I,K	—	—	—	—	—
37.41	S>>K	—	—	—	—	—
38.87	S>>K	—	—	—	—	—

Biology

Depth (m)	Coral	Algae	Mollusks	Bryozoa	Foraminifera
0.07	*	—	—	—	—
0.72	*	*	*	—	—
10.8	*	*	*	*	*
14.2	—	*	—	—	X

Key to Table 17

Mineralogy:
- C: Calcite
- A: Aragonite
- S: Silicates
- K: Clay minerals
- I: Iron minerals

Cements: Type/Origin

Type:
- VF: void-filling sparry calcite
- N: neomorphically derived sparry calcite
- AA: aragonitic

Origin:
- fp: freshwater phreatic

Porosity: Degree/Development

Development:
- M: moldic
- GF: growth framework
- V: vuggy
- I: intraparticle

Degree:
- Abundant porosity: A
- Moderate porosity: M

Biota:
- * abundant
- X present
- — absent

HOLES 4 AND 4A

Hole 4 was drilled in a saddle between two coral knolls. The saddle was covered with a thin blanket of carbonate sand derived from the adjacent overwash sand bank that bounds the barrier reef and lagoon in that area (Fig. 1). After about 9 m of drilling, the drill platform was moved about 6 m to the SE and hole 4A was started. The platform was moved because the original position required anchoring in sand, which did not hold in strong wind. The repositioning allowed securing 3 of the 4 anchors on coral heads and the hole was completed to 31 m. The water depth is 2 m.

Lithology

A 23-m thick carbonate section consists of bioclastic and framework reefal limestone interbedded with carbonate sand (Fig. 5; Plate 2A). The intervals of no recovery (Fig. 5) are probably sand layers in the upper part of the section and sand layers and/or solution cavities in the lower part of the carbonate section. The carbonate section overlies about 3 m to 4 m (23 m to 26.5 m subbottom depth) of brown mud as determined from mud coating the core barrel; none was recovered in the cores. This mud is similar to the brown mud that immediately overlies basalt in Hole 3. From 26.5 m to 31 m, where drilling was stopped, occur highly altered to fresh alkalic basalt and nephelinite laced with calcite veins and containing vesicles filled with calcite and zeolites (Plate 3A). Several flow units were recovered. A few ultramafic xenoliths are present. The basalt was probably erupted in a submarine environment.

Mineralogy

Three mineralogic zones occur in the 23-m carbonate section: from 0 m to 6.5 ±0.5 m is predominantly aragonite; from 6.5 ±0.5 m to 11 ±0.5 m calcite with some aragonite; and from 11 ±0.5 m to 23 m calcite is the sole carbonate mineral (Table 18).

The calcite-laced highly altered basalt flows in the upper part of the basalt section do not contain primary minerals. Secondary alteration products include smectite, goethite, and hematite. These are probably also the main constituents of the overlying brown mud. Fresher basalts contain primary pyroxene, olivine, nepheline, and magnetite and secondary smectite and kaolinite. Vesicles are filled with a mixture of zeolites including natrolite, thomsonite, and mesolite.

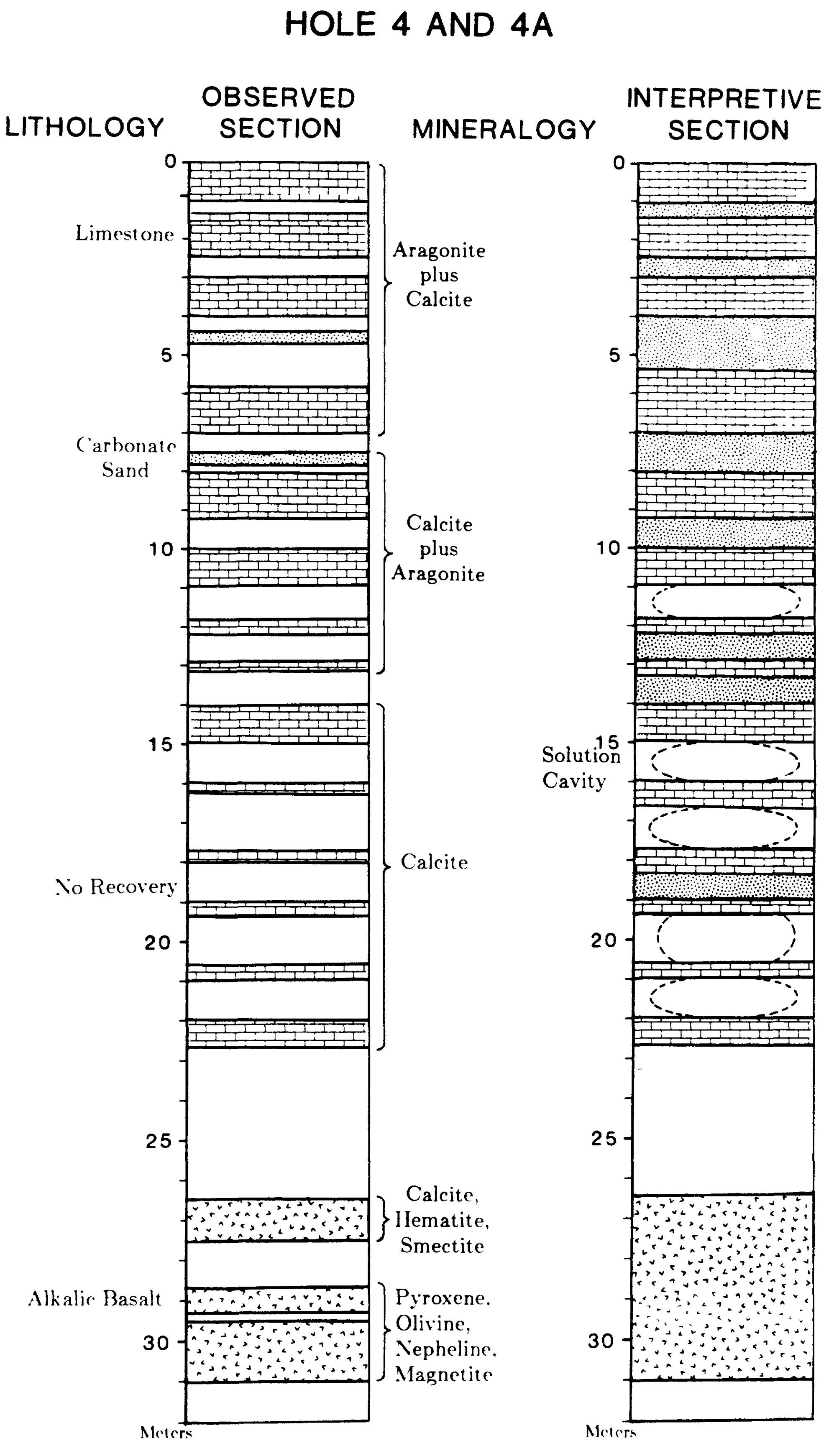

Figure 5. Stratigraphic section, general mineralogy corresponding to each lithology, and interpretive section for Holes 4 and 4A.

Table 18. Mineralogy determined by x-ray diffraction for drill cores from Holes 4 and 4A, Aitutaki, Cook Islands.

Sample No.[1]	Major[2]	Moderate	Minor or Trace
4-2-116	Aragonite		Calcite
4-3-149	Aragonite		Calcite?
4-7-705	Aragonite		Calcite?
4A-4-570	Aragonite		Calcite?
4A-4-587	Aragonite		Calcite
4A-5-710	Calcite	Aragonite	
4A-6-879	Calcite	Aragonite	
4A-7-1019	Calcite		Aragonite
4A-8-1154	Calcite		
4A-8-1159	Calcite		
4A-9-1310	Calcite		
4A-10-1444	Calcite		
4A-12-1764	Calcite		
4A-15-2258	Calcite		
4A-15-2275	Calcite		
4A-18-2747a	Calcite		Hematite Magnetite Smectite
4A-18-2747b	Calcite		Hematite Magnetite Smectite
4A-19-2853	Calcite	Goethite Magnetite Smectite Hematite Pyroxene Apatite Mixed layer clay minerals	
4A-19-2863	Pyroxene	Olivine Plagioclase Natrolite/Thomsonite Anatase	Kaolinite Smectite K-feldspar?
4A-19-2881	Pyroxene	Natrolite/Mesolite/Thomsonite Olivine	Kaolinite Smectite
4A-20-2945	Pyroxene	Natrolite/Thomsonite Olivine	Kaolinite Smectite
4A-20-2966	Pyroxene Calcite	Natrolite/Thomsonite	

Sample No.[1]	Major[2]	Moderate	Minor or Trace
4A-20-3034	Natrolite/ Mesolite/ Thomsonite		Kaolinite

---

[1] First number in sample number is hole number; second number is core number; third number is distance in centimeters from top of hole (seafloor). In some cores recovery was small and the core position in the hole was arbitrarily placed, so the third number is as we wrote before. This is common for samples in Hole 6 and for four samples in Hole 5.

[2] Roughly, major is >25%, moderate is 5-25%, and minor or trace is <5% (weight percent).

Chemical Composition

As with the previous cores, the limestones are very pure carbonates. Sr is lost as aragonite is replaced by calcite (Table 19). The composition of the highly altered basalt (4A-18-2747) in Table 19 is dominated by the large number of calcite veins that were impossible to separate from the analyzed sample. The other two basalt compositions confirm that they are moderately altered nephelinite.

Table 19. Chemical composition of limestone and basalt from Holes 4 and 4A, Aitutaki, Cook Islands.

	4-2-116	4A-6-879	4A-10-1444	4A-15-2258		4A-18-2747	4A-19-2863	4A-20-2945
SiO_2 (wt. %)	<0.10	0.49	0.10	0.35	SiO_2	18.9	38.6	39.3
Al_2O_3	0.02	0.38	0.23	0.35	Al_2O_3	9.37	10.6	10.7
Fe_2O_3	—	0.08	0.08	0.10	Fe_2O_3	10.0	6.85	6.30
FeO	0.11	<0.02	<0.02	0.05	FeO	0.61	5.36	6.04
MgO	0.59	0.77	0.86	0.65	MgO	1.48	12.9	12.6
CaO	54.0	55.3	55.8	55.8	CaO	28.5	13.2	13.4
Na_2O	0.40	<0.15	0.08	0.07	Na_2O	0.82	2.10	2.44
K_2O	<0.02	<0.02	<0.02	<0.02	K_2O	0.23	0.91	0.40
TiO_2	<0.02	0.03	<0.02	0.05	TiO_2	2.15	2.46	2.52
P_2O_5	0.02	0.06	0.1	0.08	P_2O_5	1.00	1.09	1.13
MnO	0.001[‡]	0.002[‡]	0.004[‡]	0.004[‡]	MnO	0.10	0.18	0.19
H_2O^-	0.15	0.06	0.03	0.04	H_2O^-	3.62	1.03	0.83
H_2O^+	1.86	0.47	0.29	0.43	H_2O^+	3.99	4.31	4.62
CO_2	43.8	44.9	45.2	44.8	CO_2	21.0	0.30	0.18
LOI	44.3	43.8	43.8	43.5	LOI	27.5	5.37	5.14
Total[†]	99.44	100.91	101.05	101.00	Total[†]	100.66	99.62	100.16
Ba (ppm)	9	12	12	13	As (ppm)	<10	<10	<10
Ce	<4	<4	<4	<4	Ba	430	1000	540
Co	1	1	1	2	Be	2	2	2
Cr	3	21	26	19	Cd	2	2	2
Cu	6	3	2	2	Ce	140	150	160
La	<2	<2	<2	<2	Co	48	66	64
Li	<2	<2	<2	<2	Cr	210	320	320
Mo	<2	<2	<2	<2	Cu	46	42	42
Nd	<4	<4	<4	<4	Eu	4	4	5
Ni	3	6	4	6	Ga	18	20	21
Sc	<2	<2	<2	<2	La	80	81	87
Sr	7300	1700	680	1200	Li	38	13	14
V	3	4	2	4	Mo	<2	2	<2
Zn	19	3	8	5	Nb	12	18	24
					Nd	65	71	74
					Ni	150	250	240
					Pb	9	11	9
					Sc	15	21	20
					Sr	620	1700	1700
					Th	13	11	14
					V	120	160	170
					Y	28	29	31
					Yb	2	2	2
					Zn	110	120	120
Lithology	cemented reefal debris, limestone	grayish-white porous reefal limestone	grayish-white, reefal limestone	gray and brown dense, reefal limestone fragments		very highly altered, calcite-veined alkalic basalt	moderately altered nephelinite	moderately altered nephelinite

All analyses were performed by U.S. Geological Survey analytical laboratories in Denver, Colorado and Menlo Park, California. Ten major oxides analyzed by wavelength dispersive x-ray fluorescence spectroscopy, Denver and Menlo Park. Analytical expertise provided by J. Taggart, A. Bartel, D. Siems, R. Lerner, B. King, D. Vivit, and M. Dyslin. Minor and trace elements analyzed by inductively coupled plasma atomic emission spectroscopy, Denver. Analytical expertise provided by P. Briggs, and B. Anderson. FeO, CO_2, and water determined by wet chemical methods, Menlo Park. T. Fries, L. Espos, and S. Neil provided analytical expertise.

— not detected.

[†] Totals based on LOI (loss on ignition) at 900 °C.

[‡] Value reported is from emission spectroscopy data.

For the four carbonate samples the following elements were analyzed but were below detection limits (in ppm): Ag <2; As <10; Au <8; Be <1; Bi <10; Cd <2; Eu <2; Ga <4; Ho <4; Nb <4; Pb <4; Sn <10; Ta <40; Th <4; U <100; Y <2; and Yb <1.

For the three basalts the following elements were analyzed but were below detection limits: Ag <2; Au <8; Bi <10; Ho <4; Sn <10; Ta <40; U <100.

Stable Isotopic Composition of Calcite

Secondary calcite veins and vesicle fill in the basalt have $\delta^{13}C$ and $\delta^{18}O$ values comparable to values for secondary calcite in other holes (Table 20). $\delta^{13}C$ averages -13.2$^0/_{00}$ and is the lowest average value indicating that somewhat more of the carbon was derived from organic matter than in the other holes. $\delta^{18}O$ averages 25.4$^0/_{00}$ and the significance of the $\delta^{18}O$ values is the same as for the calcites in the other holes.

Table 20. Carbon and oxygen isotopic compositions of calcite from Hole 4A, Aitutaki, Cook Islands.

Sample No.	$\delta^{13}C$ PDB	$\delta^{18}O$ SMOW	Mineralogy	Sample Description
4A-18-2747b	-11.7	25.3	Calcite	calcite veins in altered basalt
4A-20-2966	-14.7	25.5	Calcite	calcite filling basalt vesicles
Average Calcite	-13.2	25.4		

Analyses performed at U.S. Geological Survey isotope laboratory by Doug White.

Uranium-Series Age Dates

Uranium content is higher and thorium content is lower in all samples than they are in average carbonate rocks (Table 21). Uranium content is especially high in 4A-4-574. Excess ^{235}U occurs in the stratigraphically highest two samples. Average apparent vertical growth rates for the intervals sampled are 10.6 m/1,000 years at the surface to 0.2 m/1,000 years at the base. The overall, average rate for the early Holocene is 0.9 m/1,000 years. Using the minimum age (3,900 years) for the upper 7 m of section, yields a reasonable average vertical growth rate of 1.8 m/1,000 years.

Table 21. Uranium and thorium contents and U-series apparent ages of coral from Holes 4 and 4A, Aitutaki, Cook Islands.

Lab No.	Field No.	U ppm	Th ppm	$\frac{^{234}U}{^{238}U}$	$\frac{^{230}Th}{^{232}Th}$	$\frac{^{230}Th}{^{234}U}$	U/Th age 1,000 years	Corrected age 1,000 years	Coral Types and Comments	Mineralogy (XRD)*
654	4-3-179	2.694±0.065	—	1.109±0.025	—	—	Recent	—	Excess ^{235}U; *Favia* sp.	A(c?)
655	4A-4-574	6.430±0.198	0.288±0.288	1.109±0.029	1.301±1.719	0.017±0.015	1.9±1.7	0.4±1.7	Excess ^{235}U; *Leptoria*	A(c?)
656	4-7-705	2.620±0.097	0.228±0.228	1.170±0.042	8.773±4.000	0.092±0.034	$10.5^{+4.1}_{-4.0}$	$7.8^{+4.0}_{-3.9}$	*Psammocora*	A(c?)
657	4A-15-2275	2.642±0.107	0.285±0.285	1.056±0.045	26.566±26.753	0.892±0.148	≥135	—	*Favia*	C

*	Major	Moderate	Minor or Trace
Aragonite	A	(A)	(a)
Calcite	C	(C)	(c)

Petrography

Hole 4 Core 2 Depth 1.16 m
Mineralogy (XRD): Aragonite; minor calcite.
Classification: Coral Boundstone, Biolithite.

Unaltered coral and an encrusting calcareous red algae comprise this sample. An early episode of fibrous to acicular isopachous aragonite cement lines many pores (Plate 17A). This early episode of cementation within the marine phreatic zone was followed by infilling with clastic micrite (Plate 17A). The clastic micrite is made up of carbonate mud and pellets. Porosity is moderate to high with growth-framework > intraparticle.

Hole 4 Core 3 Depth 1.49 m
Mineralogy (XRD): Aragonite.
Classification: Coral Boundstone, Biolithite.

Unaltered coral contains ubiquitous fine borings. Prismatic aragonite lines the majority of the pore spaces. Botryoidal cement lines some pores (for example, see Plate 17B). Fine-grained calcarenite partly infills a few pores and is situated below the gravity cement. Porosity is moderate to high with growth-framework > intraparticle.

Hole 4A Core 4 Depth 5.70 m
Mineralogy (XRD): Aragonite.
Classification: Coral Boundstone, Biolithite.

Unaltered framework coral is capped by a thin layer of encrusting calcareous red algae which binds benthic foraminifera and other clasts. The red algae in turn is capped by a coarse- to medium-grained calcilutite. Pellets of micrite partly infill most pores. Only two smaller pore spaces are rimmed by fibrous-prismatic cement. Minute bore holes infilled with micrite are abundant throughout the coral skeleton. Growth-framework porosity is high.

Hole 4A Core 4 Depth 5.87 m
Mineralogy (XRD): Aragonite; trace calcite.

Classification: Coral Boundstone, Biolithite.

Unaltered coral, encrusted by *Millepora* on one margin, is predominant. Clastic micrite partly fills many voids, and contains fragments of bivalves, pelagic foraminifera, calcareous red algae, pellets, and gastropods. Mesopore-size channels and vugs are common and result from bioerosion or dissolution. Many pores are partly or completely filled by aragonitic botryoidal cement (Plate 17B), suggesting syndepositional cementation. Channels and vugs produce moderate porosity.

Hole 4A Core 5 Depth 7.10 m
Mineralogy (XRD): Major calcite; moderate aragonite.
Classification: *Halimeda* Packstone, Packed Biomicrite.

Halimeda plates predominate and many underwent dissolution or were partly replaced with sparry calcite. Micritized fragments of bivalves, benthic foraminifera, echinoderm spines, calcareous red algae, worm tubes, and skeletal grains are also present. Extensive selective dissolution left several free-standing micrite envelopes (Plate 18A) and voids within shell fragments. Sparry calcite fills voids between grains and within grains. Thin rims of equant sparry calcite also line many micrite envelope margins. This suggests dissolution occurred before cementation in a freshwater phreatic environment. Porosity is moderate to extensive with mesopore vuggy > interparticle > intraparticle > moldic.

Hole 4A Core 6 Depth 8.79 m
Mineralogy (XRD): Major calcite; moderate aragonite.
Classification: Coral Boundstone, Biolithite.

Framework coral completely neomorphosed to large crystals of calcite. Calcareous red algae encrusting one margin of the coral trapped benthic foraminifera, bryozoan fragments, and clastic micrite. Many of the pores are partly or completely filled with void-filling spar. Porosity is moderate with growth-framework > small megapore vuggy.

Hole 4A Core 10 Depth 14.44 m
Mineralogy (XRD): Calcite.
Classification: Skeletal Packstone, poorly washed Biosparite.

Grains include massive branching and encrusting calcareous red algae, large and small benthic foraminifera, pelagic foraminifera, echinoderms, pellets, small nearly complete gastropod shells, bivalves, bryozoa, and ostracodes. Some shell fragments neomorphosed to large calcite crystals while others maintained primary low-Mg calcite prisms. Clastic micrite surrounds many smaller grains and extensively neomorphosed micrite occurs throughout. Grains surrounded by void-filling sparry calcite were first lined by prismatic isopachous cement. This texture indicates an early episode of cementation within the marine subsurface environment followed by further cementation within the freshwater phreatic zone. Even though a variety of recognizable skeletal fragments exists, a large number of fragments were completely dissolved and then the molds infilled with sparry calcite. Porosity is moderate to high with small megapore vuggy > large mesopore channel > interparticle > moldic.

Hole 4A Core 15 Depth 22.58 m
Mineralogy (XRD): Calcite.
Classification: Skeletal Packstone, Biomicrite.

Extensive diagenesis masks many of the original biota. Identifiable grains include calcareous red algae, benthic foraminifera, echinoderm spines and plates, mollusk shell fragments, pellets, and possibly fragments of bryozoa (Plate 18B). About 50% of the original grains dissolved leaving a micrite envelope that subsequently infilled with sparry calcite. The interior of some grains is lined with an early isopachous cement of acicular crystals. This indicates an episode of submarine cementation predating the void-filling sparry calcite. Extensive neomorphism further altered the grains. Porosity is moderate with large mesopore vuggy $>>$ interparticle.

Hole 4A Core 18 Depth 27.47 m
Mineralogy (XRD): Major calcite; minor hematite, magetite, smectite.
Classification: Altered Basalt laced with Calcite Veins.

Highly altered vesicular basalt with vesicles filled with void-filling sparry calcite and anastomosed with calcite-filled fractures. Phenocrysts of olivine altered to hematite and glass altered to clay minerals.

Hole 4A Core 19 Depth 28.63 m
Mineralogy (XRD): Major pyroxene; moderate olivine, plagioclase, natrolite/thomsonite, anatase; minor kaolinite, smectite.
Classification: Basalt.

Phenocrysts of olivine occur in a groundmass of small pyroxene and plagioclase crystals and altered glass. Olivine partly altered to thomsonite and clay minerals. Patches in the groundmass are altered to chlorite and clay minerals. Thomsonite replaces plagioclase. Natrolite fills voids created by dissolution of glass.

Hole 4A Core 20 Depth 29.45 m
Mineralogy (XRD): Major pyroxene; moderate natrolite/thomsonite, olivine; minor kaolinite, smectite.
Classification: Nephelinite.

Phenocrysts of olivine occur in a groundmass of pyroxene, nepheline, and plagioclase. Crystals are larger and alteration is more extensive in this sample than in the previous sample. This nephelinite probably erupted in a submarine environment.

Summary of Holes 4 and 4A

The stratigraphic section at Holes 4 and 4A consists of 23 m of limestone and carbonate sand, 4 m of brown mud derived from the weathering and leaching of volcanic rocks, and 4 m of nephelinite and alkalic basalt flows.

In the carbonate section, framework coral is the dominant component in the upper 7 m of core (zone 1); algae, foraminifera, echinoderms, and bryozoa are common throughout the rest of the core (Table 22). The carbonate section is divided into 3 zones based on diagenetic features.

Zone 1, 0 m to 6.5 ±0.5 m, consists primarily of skeletal aragonite with some acicular aragonite cement and abundant primary growth-framework and intragranular porosity. The aragonite is rich in Sr and the age of the bottom of the zone is about $7{,}800^{+4{,}000}_{-3{,}900}$ years, probably the lower end of this range, such as 3,900 years.

Zone 2, 6.5 ±0.5 m to 11 ±0.5 m, consists of calcite with minor aragonite. Freshwater void-filling cement is common and calcite underwent neomorphism. Moderate porosity results from primary intragranular, intergranular, growth-framework pores, and secondary vugs. Sr decreased as aragonite was replaced by calcite.

Zone 3, 11 ±0.5 m to 23 m, consists of calcite replaced reefal limestone containing freshwater phreatic cement overprinting marine phreatic void-filling cement. Calcite underwent neomorphism. Abundant to moderate secondary vuggy porosity developed.

Data are not available for the brown mud that underlies the limestone and overlies the basalt. The alkalic basalt and nephelinite at the base of the section probably erupted in a marine environment. The basalt is laced with calcite veins and vesicles are filled with calcite and zeolites. The calcite formed under predominantly freshwater conditions and the carbon was derived from both organic matter and seawater. The basalt is basement rock and is probably continuous with flows exposed on Motu Rapota.

Table 22. Summary of petrography, Holes 4 and 4A.

Geology

Depth (m)	Mineralogy	Major Diagenetic Fabrics	Minor Diagenetic Fabrics	Major Porosity Types	Minor Porosity Types	Degree of Porosity
1.16	A>>C	AA	—	GF	I	M-A
1.49	A>>C	AA	—	GF	I	M-A
5.7	A>>C	AA	—	GF	—	A
5.87	A>>C	AA	—	GF	C,V	M
7.1	C>A	VF/fp	—	V	I,i,M	M-A
8.79	C>A	N	VF/fp	GF	V	M
14.44	C	VF/fp	VF/mp,N	V	C,i,M	M-A
22.58	C	VF/fp,N	VF/mp	V	i	M
27.47	C>S,I,K	VF/fp	—	—	—	—
28.63	S>K,I	—	—	—	—	—
29.45	S>K	—	—	—	—	—

Biology

Depth (m)	Coral	Algae	Mollusks	Echinoderms	Bryozoa	Foraminifera
1.16	*	X	—	—	—	—
1.49	*	—	—	—	—	—
5.7	*	*	—	—	—	X
5.87	*	X	X	—	—	X
7.1	—	*	X	X	—	X
8.79	*	*	—	—	X	X
14.44	—	*	*	*	X	*
22.58	—	*	*	*	*	*

Key to Table 22

Mineralogy:
- C: Calcite
- A: Aragonite
- S: Silicates
- K: Clay minerals
- I: Iron minerals

Cements: Type/Origin

Type:
- VF: void-filling sparry calcite
- N: neomorphically derived sparry calcite
- AA: aragonitic

Origin:
- mp: marine phreatic
- fp: freshwater phreatic

Porosity: Degree/Development

Development:
- M: moldic
- GF: growth framework
- V: vuggy
- I: intraparticle
- i: interparticle
- C: channel

Degree:
- Abundant porosity: A
- Moderate porosity: M

Biota:
- * abundant
- X present
- — absent

HOLE 5

Hole 5 is located between Motu Ee and Aitutaki Island (Fig. 1). We chose this site in order to drill beneath a basin (sinkhole?) lying in a water depth of 8.5 m. The basin is surrounded by coral heads on which the platform was anchored. The floor of the basin consists of white soupy carbonate mud. The upper 10 m of carbonate sand, silt, and mud were recovered by pushing a 7-cm-diameter plastic core liner down a larger diameter sand pipe. Two 5-m-long cores were taken; each 5-m core was cut into 1-m intervals when retrieved from the hole and placed on the platform. The upper 3 m were soupy and flowed out of the core liner.

Lithology

The upper 16.3 m is composed of silty and sandy carbonate mud made up of reefal detritus (Fig. 6). Several meter-thick sections are graded from pebble and coarse sand-sized shell hash to carbonate mud at the top of the intervals. From 16.3 m to 22 m, the sandy carbonate silt and mud contains pebbles of reefal debris. Between 22 m and 22.5 m is a bed of greenish-black, organic-rich mud, a swamp deposit. Between 23.5 m and 27 m is an interbedded sequence of bioclastic limestone and yellow-brown to greenish-brown mud, some layers containing pebbles of reefal debris. From 27.5 m to 44 m occurs volcanogenic deposits, mostly silt and mud derived from the intense weathering (pedogenic) of basaltic rocks. From 44 m to 47.5 m occurs highly to moderately weathered alkali olivine basalt, probably erupted subaerially. From 47.5 m to 53 m occurs recrystallized limestone that is replaced by dolomite in places. Solution cavities or sand layers separate the limestone beds.

Mineralogy

The upper 22 m of carbonate sediment is composed predominantly of aragonite with variable amounts of calcite (Table 23). Pyrite, evaporite minerals, and organic matter make up the greenish-black mud. Organic carbon is 32.5% and sulfur is 9.69% of the deposit (Table 24, sample 5-11a-2230). The pyrite and organic carbon indicate a reducing environment, and we suggest a swamp deposit or stagnant island pond that underwent evaporation and accumulation of salts. The limestone bed is composed of calcite and the interbedded mud layers are kaolinite, goethite, and nordstrandite, a mineral suite similar to the one that occurred on the floors of solution cavities in Hole 2. The completely weathered volcanogenic section contains a variety of clay minerals and iron minerals, but no primary basalt minerals other than magnetite; all the other minerals are secondary. The alkali olivine basalt consists of primary pyroxene, olivine, and magnetite with a whole host of secondary minerals (Table 23). The lowermost section is limestone composed of calcite and some dolomite. The dolomite is protodolomite with excess calcium in the crystal structure (Table 25). Dolomite is minor in Hole 5 compared with Hole 2 because in Hole 5 impermeable basalt caps the limestone section, inhibiting the flow of large amounts of seawater through the section, which would otherwise have provided the magnesium needed for pervasive dolomitization.

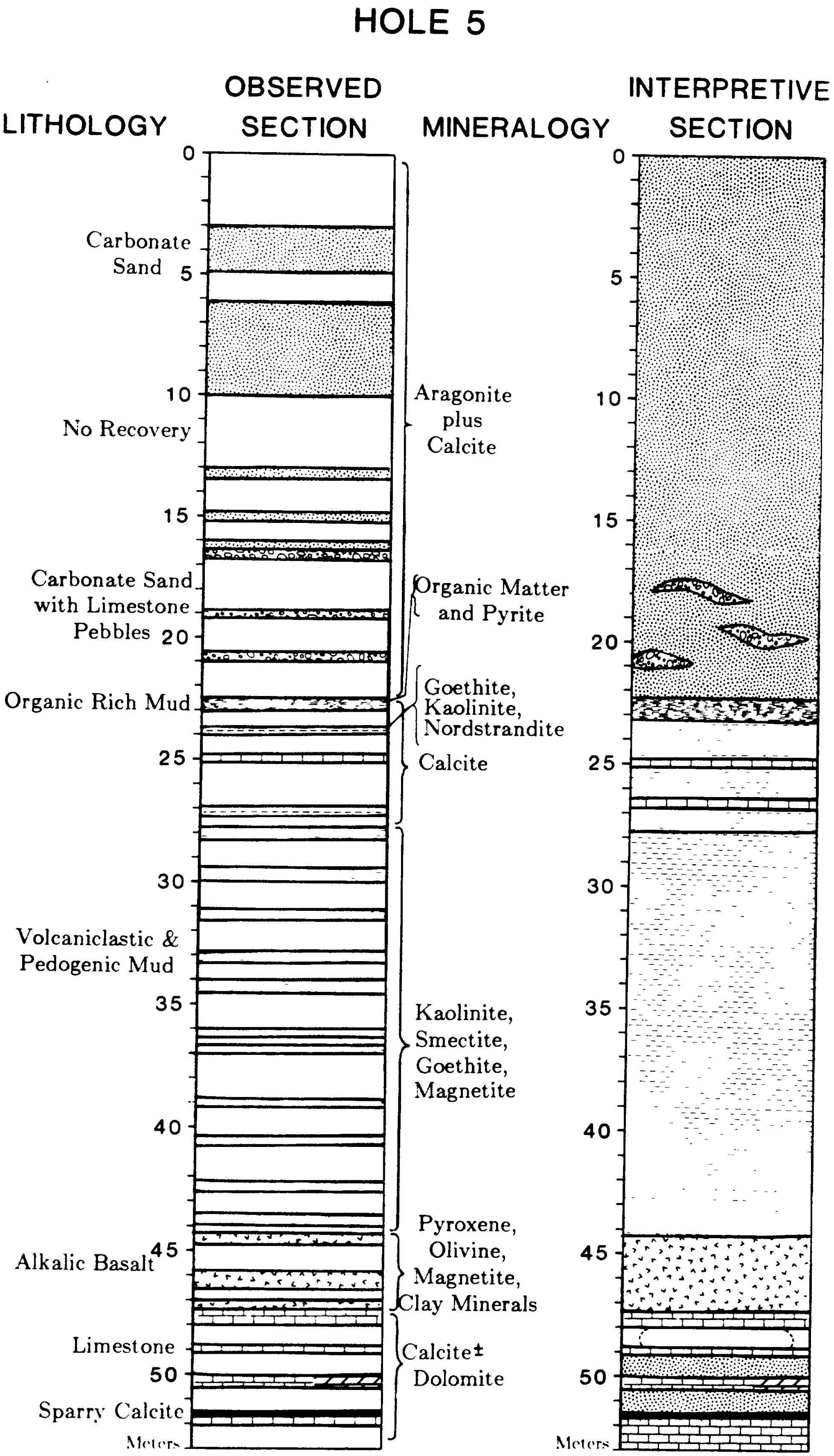

Figure 6. Stratigraphic section, general mineralogy corresponding to each lithology, and interpretive section for Hole 5.

Table 23. Mineralogy determined by x-ray diffraction for drill cores from Hole 5, Aitutaki, Cook Islands.

Sample No.[1]	Major[2]	Moderate	Minor or Trace
5-1-4-305	Aragonite	Calcite	
5-1-4-315	Aragonite	Calcite	
5-2-5-950	Aragonite	Calcite	
5-8-1693	Aragonite Calcite		
5-9A-1934	Aragonite	Calcite	
5-9A-1934B	Aragonite Calcite		
5-10A-2083	Aragonite	Mg-Calcite Calcite	Pyrite Halite Kaolinite Gypsum Goethite?
5-11a-2230	Pyrite	Halite Kaolinite	Gypsum Anhydrite?
5-12A-2395	Kaolinite Goethite Magnetite	Nordstrandite[3] Calcite	Analcime?
5-13-2507	Calcite		
5-14A-2714	Goethite	Nordstrandite Kaolinite	Magnetite
5-16-2970	Kaolinite Goethite Magnetite		Analcime?
5-19A-3477	Smectite Goethite Kaolinite	Mixed layer clay minerals	Siderite?
5-22A-3918	Smectite Goethite	Celadonite Magnetite Hematite	
5-26-4468	Celadonite	Goethite Smectite Magnetite Apatite Mixed layer clay minerals	Hematite? Kaolinite?
5-27-4640	Pyroxene	Calcite Smectite	Celadonite Magnetite Olivine Goethite Apatite Plagioclase? K-feldspar? Natrolite?
5-28-4764	Celadonite Pyroxene Magnetite	Apatite Plagioclase K-feldspar?	Hematite? Natrolite?

Sample No.[1]	Major[2]	Moderate	Minor or Trace
	Goethite		
	Smectite		
5-28-4776	Calcite		Dolomite?
5-29-4922	Calcite		Dolomite?
5-31-5202	Calcite	Dolomite[4]	
5-31-5211	Calcite		

[1] First number in sample number is hole number; second number is core number; third number is distance in centimeters from top of hole (seafloor). In some cores recovery was small and the core position in the hole was arbitrarily placed, so the third number is as we wrote before. This is common for samples in Hole 6 and for four samples in Hole 5.

[2] Roughly, major is >25%, moderate is 5-25%, and minor or trace is <5% (weight percent).

[3] Formula for nordstrandite is $Al(OH)_3$.

[4] Dolomite is protodolomite with 3 to 10 mole % excess $CaCO_3$ and broad and weak ordering x-ray reflections at 2.41 Å and 2.54 Å.

Table 24. Carbon analysis of various rock types and sulfur analysis from an organic-rich mud from Hole 5, Aitutaki, Cook Islands. Values are in weight percent.

Sample No.	Total C	Organic C	Carbonate C	Total S	Lithology
5-1-4-315	12.0	0.73	11.3	—	silty carbonate mud
5-2-5-950	11.8	0.29	11.5	—	silty carbonate mud
5-11a-2230	32.5	32.5	<0.01	9.69	greenish-black organic-rich mud
5-16-2970	0.05	0.05	<0.01	—	gray volcaniclastic and pedogenic mud
5-22A-3918	0.05	0.02	0.03	—	volcaniclastic and pedogenic mud
5-27-4640	0.78	0.04	0.74	—	basalt
5-31-5202	12.2	0.44	11.7	—	dense limestone

Total C and total S determined by infrared absorption spectrophotometry. Carbonate carbon determined by coulometric titration. Organic carbon determined by difference. Analyses performed at U.S. Geological Survey analytical laboratories, Menlo Park, California. T. Fries and S. Neil provided analytical expertise.

Table 25. Mole percentage $MgCO_3$ in carbonates from Hole 5, Aitutaki, Cook Islands.

Sample No.	Mole % $MgCO_3$	Mineralogy	Comments
5-31-5202	1.5	Calcite	calcite (major)
5-31-5202	43	Dolomite[1]	dolomite (moderate)
5-31-5211	1	Calcite	

[1] Dolomite is protodolomite as defined by excess mole percentage of $CaCO_3$ and by weak and broad x-ray reflections at 2.41 Å and 2.54 Å.

Chemical Composition

The aragonite mud capping the section is very pure carbonate with high Sr content (Table 26). The recrystallized limestone that occurs at the base of the section contains some contamination by volcanogenic minerals (silicon, aluminum content), but is dominantly calcium carbonate with minor to moderate amounts of calcium-magnesium carbonate (dolomite) (Table 26).

The greenish-black mud is rich in iron, carbon, and sulfur and is predominantly organic matter and pyrite. The pedogenic muds are similar to the muds in Hole 3 and rich in aluminum, iron, titanium, chromium, and nickel as well as arsenic, barium, lithium, and thorium in places (Table 26). Several elements (such as titanium, chromium, lithium, strontium, thorium, vanadium) decrease through the pedogenic mud section into the basalt suggesting *in situ* leaching and weathering (pedogenesis) of basalt flows producing increasing concentration of the refractory elements with increasing maturity of the deposit. The one chemical analysis for basalt shows it to be highly altered alkalic basalt.

Table 26. Chemical composition of carbonate deposits (columns 1-3), and volcanogenic rocks and sediments (columns 4-8) from Hole 5, Aitutaki, Cook Islands.

	5-1-4-315[1]	5-2-5-950[1]	5-31-5202[1]		5-11a-2230	5-12A-2395	5-16-2970	5-22A-3918	5-27-4640
SiO_2 (wt. %)	<0.1	<0.1	1.1	SiO_2 (wt. %)	3.3	15.7	26.0	30.3	38.2
Al_2O_3	0.11	0.09	0.8	Al_2O_3	4.90	21.0	23.0	18.2	13.1
Fe_2O_3	0.1	0.1	0.50	Fe_2O_3	N/A	22.1*	21.4	18.6	11.0
FeO	N/A	N/A	N/A	FeO	13.5‡	N/A	0.46	0.74	2.60
MgO	2.1	1.8	5.5	MgO	1.1	1.0	0.6	1.6	5.7
CaO	52.2	52.5	47.7	CaO	1.32	7.48	0.26	2.12	10.3
Na_2O	0.40	0.45	0.24	Na_2O	3.3	1.5	0.80	1.1	1.1
K_2O	<0.05	<0.05	<0.05	K_2O	0.14	0.10	0.14	0.26	0.98
TiO_2	0.02	0.02	0.12	TiO_2	0.94	4.50	3.64	3.66	2.52
P_2O_5	0.10	0.10	0.24	P_2O_5	0.92	1.62	1.08	1.38	0.76
MnO	0.002	0.001	0.19	MnO	0.07	0.22	0.07	0.28	0.13
H_2O^-	0.62	0.39	0.36	H_2O^-	11.96	N/A	9.06	13.21	6.55
H_2O^+	1.85	1.84	0.53	H_2O^+	21.45	N/A	9.02	6.47	3.82
CO_2	41.4	42.1	42.8	CO_2	N/A‡	N/A	0.17	0.20	2.85
LOI	45.0	44.6	43.9	LOI	70.7	23.1	21.3	20.9	13.2
Total†	100.03	99.66	100.29	Total†	100.19	98.32	98.75	99.14	99.59
Ba (ppm)	10	13	81	As (ppm)	50	110	30	<10	<10
Ce	<4	<4	<4	Ba	210	710	570	210	630
Co	2	2	10	Be	1	3	4	2	2
Cr	12	12	24	Cd	<2	4	<2	<2	2
Cu	4	1	7	Ce	71	260	140	130	92
La	5	5	7	Co	110	100	58	180	64
Li	<2	<2	7	Cr	290	1000	1100	850	790
Mo	<2	<2	<2	Cu	52	56	60	75	52
Nd	<4	<4	4	Eu	<2	8	5	5	4
Ni	3	3	46	Ga	8	29	32	28	22
Sc	16	17	<2	La	43	170	70	80	58
Sr	5900	6400	180	Li	31	140	77	37	31
V	4	4	15	Mo	3	8	<2	<2	<2
Zn	<2	<2	5	Nb	N/A	N/A	N/A	N/A	N/A
				Nd	32	130	61	64	47
				Ni	330	640	690	810	570
				Pb	12	23	10	9	7
				Sc	12	41	44	32	24
				Sr	910	2200	1600	180	490
				Th	8	28	21	14	10
				V	120	310	310	220	180
				Y	20	77	41	36	28
				Yb	2	6	5	4	3
				Zn	110	170	190	220	140
Lithology	silty carbonate mud	silty carbonate mud	dense, recrystallized dolomitic limestone	Lithology	greenish-black organic-rich mud	dark yellow-brown silty pedogenic mud	gray altered pyroclastic(?) deposit, pedogenic	very altered basalt(?), pedogenic	alkalic basalt

All analyses were performed by U.S. Geological Survey analytical laboratories in Denver, Colorado and Menlo Park, California. Ten major oxides analyzed by wavelength dispersive x-ray fluorescence spectroscopy, Denver and Menlo Park. Analytical expertise provided by J. Taggart, A. Bartel, D. Siems, R. Lerner, B. King, D. Vivit, and M. Dyslin. Minor and trace elements analyzed by inductively coupled plasma atomic emission spectroscopy, Denver. Analytical expertise provided by P. Briggs, and B. Anderson. FeO, CO_2, and water determined by wet chemical methods, Menlo Park. T. Fries, L. Espos, and S. Neil provided analytical expertise.

[1] The presence of organic materials prevented the accurate determination of FeO. Total Fe reported as Fe_2O_3. CO_2 value represents carbonate carbon only. See Table C in Appendix 2 for total carbon content.

N/A not analyzed.

* Total iron reported as Fe_2O_3.

† Totals based on LOI (loss on ignition) at 900 °C.

‡ Total iron reported as FeS_2. Carbon present is primarily organic. See Table C, Appendix 2 for sulfur and carbon contents and Table 23, for mineralogy.

For the three carbonate samples the following elements were analyzed but were below detection limits (in ppm): Ag <2; As <10; Au <8; Be <1; Bi <10; Cd <2 except 5-31-5202 with 2 ppm; Eu <2; Ga <4; Ho <4; Pb <4; Sn <10; Ta <40; Th <4; U <100; Y <2; and Yb <1.

For the four volcanic and sediment samples the following elements were analyzed but were below detection limits: Ag <2; Au <8; Bi <10; Ho <4; Sn <10; Ta <40; U <100.

Stable Isotopic Compositions of Aragonite and Calcite

The isotopic composition of the aragonite mud is consistent with precipitation of carbonate from seawater (Table 27). The source of the carbon is seawater bicarbonate. The mud is composed predominantly of diminutive shell debris. Sparry calcite at the base of the hole has the same isotopic composition as the other secondary calcites from the other cores. It formed predominantly in freshwater with organic matter and seawater as sources of the carbon.

Table 27. Carbon and oxygen isotopic compositions of calcite cement and aragonite muds from Hole 5, Aitutaki, Cook Islands.

Sample No.	$\delta^{13}C$ PDB	$\delta^{18}O$ SMOW	Mineralogy SMOW	Sample Description
5-1-4-315	+3.1	29.3	Aragonite Calcite	silty carbonate mud
5-2-5-950	+2.9	29.3	Aragonite Calcite	silty carbonate mud
5-31-5211	-10.9	25.4	Calcite	sparry calcite
Average Aragonite	+3.0	29.3		
Average Calcite	-10.9	25.4		

Analyses performed at U.S. Geological Survey isotope laboratory by Doug White.

Uranium-Series Age Dates

Apparent ages of recrystallized limestone at 25 m and 49 m are $\geq$64,000 years and $\geq$88,400 years, respectively (Appendix 4). The Th content of the 25 m limestone is anomalously high. It indicates possible contamination of the limestone by the Th-rich pedogenic clays.

Petrography

Hole 5 Core 8 Depth 16.93 m
Mineralogy (XRD): Aragonite, calcite.
Classification: Coral Boundstone, Biolithite.

Thick layers of encrusting red algae cover an *Acropora* branch that was extensively bored by sponges and filamentous blue-green algae (Plate 19A). Detrital micrite and pellets of micrite and foraminifera infill framework pores. Radiating acicular aragonite crystals of the coral are unaltered. A few pores are lined or partly lined with bladed, fibrous, aragonitic void-filling isopachous cement. Intraparticle and growth-framework porosities are moderate to high.

Hole 5 Core 13 Depth 25.07m
Mineralogy (XRD): Calcite.
Classification: Grainstone, sorted Biosparite.

Moderately to well-sorted bioclasts include abundant calcareous algae, benthic foraminifera (mostly nummulites), and echinoderm spines. Gastropod fragments, *Halimeda*, and bivalve casts are also present. Micritic envelopes bound most bioclasts and molds (Plate 19B). The clasts may have been deposited in a mud matrix that underwent neomorphic inversion to calcite. Isopachous rims of fine-grained subhedral calcite crystals line both intraparticle and interparticle pores. Syntaxial overgrowths that nucleated on echinoderm fragments also infill intergranular pores. Extensive neomorphism of both the bioclasts and cements is evident. Large, equant void-filling calcite crystals of freshwater origin infill some molds. Moderate to high porosity is of several types with moldic > intraparticle > intercrystal > dissolution vugs.

Hole 5 Core 26 Depth 44.68 m
Mineralogy (XRD): Major celadonite; moderate goethite, smectite, magnetite, apatite, mixed-layer clay minerals.
Classification: Highly altered Alkalic Basalt.

Olivine phenocrysts completely altered to reddish-brown goethite. Groundmass crystals altered to a light brown material in a gray, altered glass matrix. Extensive fracturing and some dissolution is evident. This basalt probably erupted subaerially, and is similar to the flows from Hole 1.

Hole 5 Core 27 Depth ~46.40 m
Mineralogy (XRD): Major pyroxene; moderate calcite, smectite; minor celadonite, magnetite, olivine, goethite, apatite.
Classification: Moderately altered Alkalic Basalt.

Large phenocrysts that are partly to completely altered to goethite and clay minerals occur in a groundmass of altered plagioclase laths and fresh pyroxene laths (Plate 20A). Large crystals of equant, twinned, void-filling calcite infills fractures. These calcite crystals probably precipitated in a freshwater phreatic diagenetic environment.

Hole 5 Core 28 Depth 47.64m
Mineralogy (XRD): Major celadonite, pyroxene, magnetite, goethite, smectite; moderate apatite, plagioclase.
Classification: Highly altered Alkalic Basalt.

Olivine phenocrysts were either partly altered to clay minerals (fibrous texture, low relief) or completely altered to a reddish brown goethite. The groundmass shows evidence of alteration and replacement by radiating, pore-lining fibrous clay minerals. The small size of plagioclase laths indicates rapid cooling.

Hole 5 Core 28 Depth 47.76m
Mineralogy (XRD): Calcite.
Classification: Crystalline Limestone, Biosparite.

Extensive recrystallization masks biota and primary structures. Neomorphism, characterized by wavy, diffuse crystal boundaries of both primary and secondary calcite crystals, is the most prominent diagenetic feature. A few large poikilotopic cement crystals enclose smaller crystals. One calcite crystal measures 1 cm. Sparse dolomite rhombs are interspersed among calcite crystals. Large cement crystals of a freshwater phreatic origin infill large voids. Void-filling cement is not common in smaller voids. More than one generation of fracturing and channeling developed. Porosity is relatively low with intercrystalline >> vuggy.

Hole 5 Core 31 Depth 52.02 m
Mineralogy (XRD): Major calcite; moderate dolomite.
Classification: Crystalline Limestone, Biosparite

Extensive recrystallization masks biota and primary structures. Several kinds and generations of cement are identifiable. Micrite and neomorphic calcite are speckled with dolomite rhombs (Plate 20B). Void-filling cement, formed in a freshwater phreatic environment, infills large pores (Plate 21A). Poikilotopic crystals enclose smaller calcite crystals. Moderate porosity occurs with vuggy > moldic.

Hole 5 Core 31 Depth 52.11 m
Mineralogy (XRD): Calcite.
Classification: Crystalline Limestone, Biosparite.

This sample shows extensive recrystallization. Calcite microspar with thin rust-colored rims surround casts containing neomorphic calcite crystals. Large void-filling(?) calcite crystals are peppered with small patches of microspar. Some sparry calcite crystals show continuous twinning across grain boundaries. Moderate to low porosity is dominantly intercrystalline. Small dissolution vugs formed within the microspar.

Summary of Hole 5

Hole 5 consists of an upper section of carbonate sediments (0 to 22 m), a section of mixed bioclastic carbonates and volcaniclastic and pedogenic mud (22 to 27 m), pedogenic mud (27 to 44 m), subaerially erupted alkali olivine basalt (44 to 47.5 m), and recrystallized bioclastic limestone (47.5 to 53 m). This section records deposition through a falling then rising sea level: starting at the base, marine deposition, subaerial volcanism and soil development, shore-line deposition, coastal swamp deposition, and finally back to marine deposition which produced the uppermost 22 m of deposits. The upper 22 m of carbonate mud and perhaps the swamp deposit are of probable Holocene age.

Biota in the upper limestone include coral, algae, foraminifera, sponges, mollusks, and some echinoderms. Recrystallization rendered most bioclasts in the lower limestone unrecognizable (Table 28). The strong recrystallization resulted from the eruption of the immediately overlying basalt flows. These same flows inhibited the flow of seawater through the limestone, which in turn inhibited the pervasive dolomitization of the lowermost limestones, as occurred at Hole 2.

Carbonate mineralogy changes from aragonite in the upper 22 m of section to calcite below this depth, with some dolomite in the lowermost limestone. The pebbles of aragonite limestone within the aragonite mud show only minor marine phreatic void-filling cementation and moderate to high primary growth-framework porosity (Table 28). Throughout the stratigraphically lower limestones, neomorphic grain replacement and some freshwater phreatic void-filling cementation occurred. Limestones above the basalt have greater prosity than those below. Dolomite may have formed in a zone of mixed fresh and marine pore waters.

Table 28. Summary of petrography, Hole 5.

Geology

Depth (m)	Mineralogy	Major Diagenetic Fabrics	Minor Diagenetic Fabrics	Major Porosity Types	Minor Porosity Types	Degree of Porosity
16.93	A>C	AA	—	GF	I	M-A
25.07	C	N	VF/fp	M	I,X,V	M-A
44.68	S>I,K	—	—	—	—	—
46.4	S>C,I,K	—	VF/fp	—	F	—
47.64	S,I,K	—	—	—	—	—
47.76	C>>D	N	VF/fp	X	V	m
52.02	C>D	D,N	Pk,VF/fp	V	M	M
52.11	C	N	VF	X	V	m-M

Biology

Depth (m)	Coral	Algae	Mollusks	Echinoderms	Foraminifera	Sponges
16.93	*	*	—	—	X	X
25.07	—	*	*	*	*	—

Key to Table 28

Mineralogy:
- C: Calcite
- A: Aragonite
- D: Dolomite
- S: Silicates
- K: Clay minerals
- I: Iron minerals

Cements: Type/Origin

Type:
- VF: void-filling sparry calcite
- N: neomorphically derived sparry calcite
- AA: aragonitic
- D: dolomitization
- Pk: poikilotopic overgrowth

Origin:
- fp: freshwater phreatic

Porosity: Degree/Development

Development:
- M: moldic
- GF: growth framework
- V: vuggy
- I: intraparticle
- F: fracture
- X: intercrystal

Degree:
- Abundant porosity: A
- Moderate porosity: M
- Minor porosity: m

Biota:
- * abundant
- X present
- — absent

HOLE 6

Hole 6 was drilled in order to complete a transect between Holes 4 and 5. It was drilled on the flat, sand-covered lagoon floor adjacent to a coral pinnacle in about 3 m of water (Fig. 1). The area is bathymetrically and structurally representative of a large area of the lagoon floor.

Lithology

The upper 14 m of section consists of interbedded framework or bioclastic limestone with carbonate sand; the limestone is cut in places by solution cavities (Fig. 7). From 14 m to 20.5 m is highly altered volcanogenic debris cemented by calcite and cut by calcite veins. Calcite is the dominant constituent in most of this interval. From 20.5 m to 21 m is moderately altered alkali olivine basalt that erupted in a marine environment. The same lithology immediately overlying the basalt also occurs for a half meter below the basalt. From 21.5 m to 30 m is recrystallized limestone with several sparry calcite cement layers.

Mineralogy

The uppermost 9 ±1 m of section is composed of a variable mixture of aragonite, calcite, and Mg-calcite, whereas the bottom 5 m of the 14 m limestone section is calcite (Table 29). The altered volcanic debris (14 to 20.5 m) is composed predominantly of calcite (cement, veins, replacement) and kaolinite, goethite, and magnetite. These last three minerals comprise the pedogenic muds from the other sites (Holes 1, 3, 4, 5). The large amount of calcite in this interval indicates that the permeability was greater at Hole 6 than at the other holes and that carbonate was mobilized from elsewhere in the section and reprecipitated within the pedogenic section. The basalt contains primary pyroxene, plagioclase, and olivine and secondary smectite, K-feldspar, and amphibole (Table 29). Limestone below the basalt is composed of calcite with little or no magnesium in the crystal structure (Tables 29 and 30).

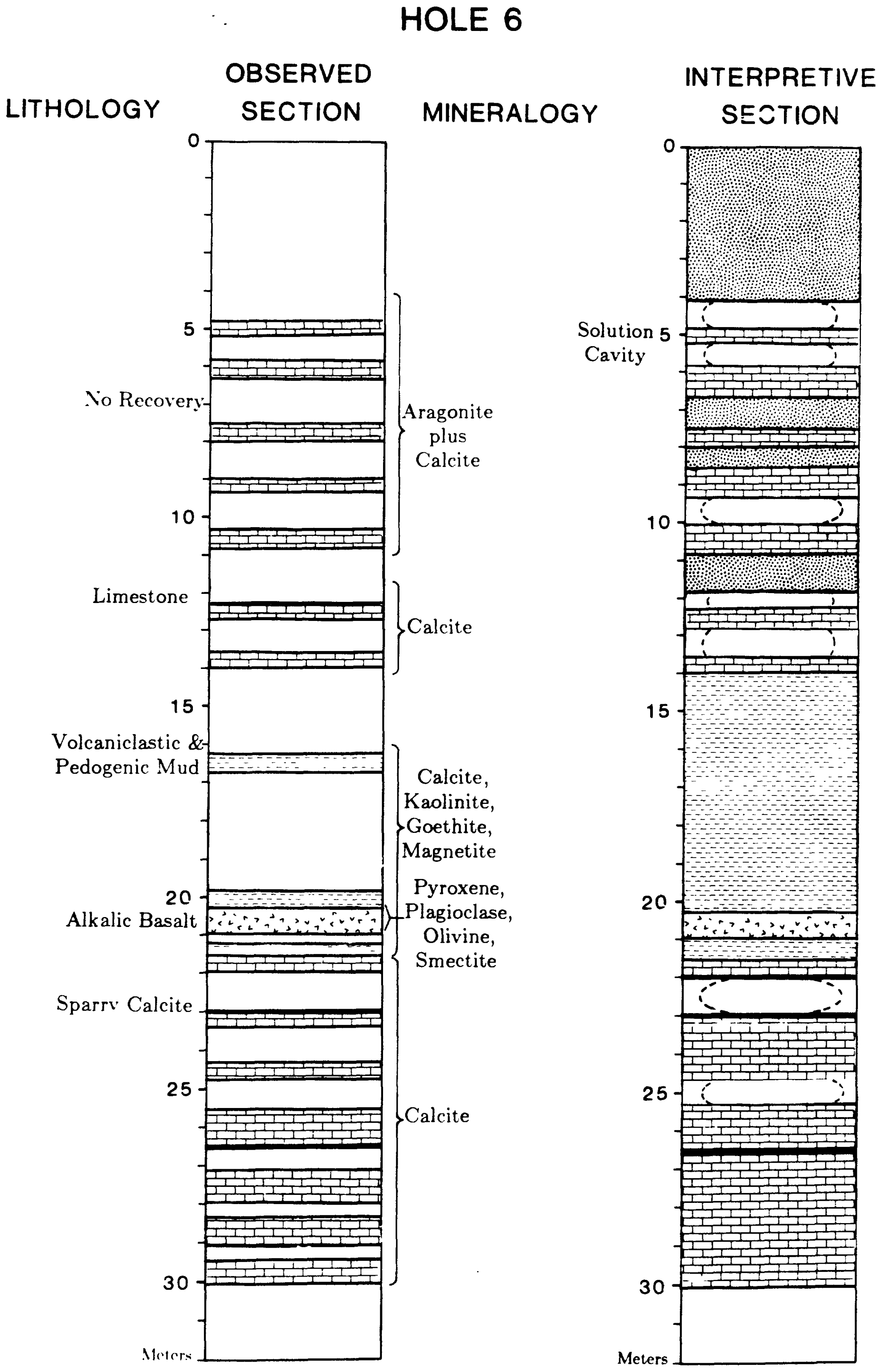

Figure 7. Stratigraphic section, general mineralogy corresponding to each lithology, and interpretive section for Hole 6.

Table 29. Mineralogy determined by x-ray diffraction for drill cores from Hole 6, Aitutaki, Cook Islands.

Sample No.[1]	Major[2]	Moderate	Minor or Trace
6-1-488	Aragonite		Calcite Mg-Calcite
6-2-693	Aragonite		Calcite
6-3-775-I	Calcite Aragonite Mg-Calcite		
6-3-775-II	Mg-Calcite Aragonite	Calcite	
6-3-779	Calcite Aragonite	Mg-Calcite	
6-4-929	Calcite		Aragonite?
6-5-1085	Calcite		Aragonite?
6-6-1244	Calcite		
6-9-1708a	Calcite	Kaolinite Goethite Magnetite	
6-9-1708b	Calcite		Kaolinite Goethite
6-11a-1993	Calcite		Kaolinite Goethite Magnetite?
6-12-2040	Calcite		Kaolinite Goethite Magnetite? Apatite?
6-12-2054	Pyroxene	Plagioclase K-feldspar Olivine Smectite	Kaolinite Amphibole Natrolite? Analcime?
6-13-2146	Calcite		Kaolinite Smectite Goethite Magnetite?
6-13-2160	Calcite		
6-14-2308	Calcite		
6-16-2605	Calcite		
6-17-2657	Calcite		
6-17-2660	Calcite		
6-18-2752	Calcite		
6-18-2763	Calcite		
6-19-2902	Calcite		

Sample No.[1]	Major[2]	Moderate	Minor or Trace
6-19-2910	Calcite		
6-19-2934	Calcite		

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[1] First number in sample number is hole number; second number is core number; third number is distance in centimeters from top of hole (seafloor). In some cores recovery was small and the core position in the hole was arbitrarily placed, so the third number is as we wrote before. This is common for samples in Hole 6 and for four samples in Hole 5.

[2] Roughly, major is >25%, moderate is 5-25%, and minor or trace is <5% (weight percent).

Table 30. Mole percentage $MgCO_3$ in carbonates from Hole 6, Aitutaki, Cook Islands.

Sample No.	Mole % $MgCO_3$	Mineralogy
6-14-2308	0	Calcite
6-16-2605	0	Calcite
6-17-2657	0	Calcite
6-17-2660	0	Calcite
6-18-2763	0	Calcite

Chemical Composition

Limestone from the aragonite section is very pure calcium carbonate and the aragonite contains much strontium (Table 31, analysis 1); in some places high magnesium calcite occurs with the aragonite (Table 31, analysis 2). The recrystallized limestone below the basalt is also pure calcium carbonate but with much less strontium than the younger limestone. Calcium carbonate dominates the analysis of the pedogenic deposit and masks the composition of the primary volcanic component. The basalt is an alkalic basalt that underwent a minor to moderate degree of alteration (Table 31) and is chemically identical to the flow sampled in Hole 3.

Table 31. Chemical composition of limestones (columns 1-4), and volcanogenic rocks and sediments (columns 5-6) from Hole 6, Aitutaki, Cook Islands.

	6-1-488	6-3-779	6-16-2605[1]	6-19-2934[1]		6-9-1708	6-12-2054
SiO_2 (wt. %)	<0.10	0.90	<0.1	<0.1	SiO_2 (wt. %)	7.34	43.7
Al_2O_3	0.02	0.56	0.1	0.2	Al_2O_3	4.45	11.9
Fe_2O_3	0.01	0.30	<0.1	<0.1	Fe_2O_3	2.22	2.73
FeO	<0.02	0.07	N/A	N/A	FeO	0.04	7.99
MgO	0.40	2.71	0.45	0.50	MgO	0.45	11.9
CaO	54.2	51.6	56.3	56.0	CaO	47.1	10.9
Na_2O	0.49	<0.15	0.12	0.11	Na_2O	0.23	3.3
K_2O	<0.02	<0.02	<0.05	<0.05	K_2O	0.03	1.06
TiO_2	<0.02	0.06	0.02	0.02	TiO_2	0.56	1.80
P_2O_5	0.01	0.12	0.04	0.08	P_2O_5	0.06	0.80
MnO	0.001‡	0.007‡	0.006‡	0.009‡	MnO	<0.02	0.16
H_2O^-	0.16	0.35	0.08	0.10	H_2O^-	0.66	1.12
H_2O^+	1.77	0.99	0.20	0.27	H_2O^+	2.29	1.41
CO_2	44.2	43.9	43.6	43.6	CO_2	37.2	0.64
LOI	44.4	43.5	43.6	43.7	LOI	38.4	2.88
Total†	99.53	99.83	100.64	100.62	Total†	100.88	99.12
Ba (ppm)	27	21	6	8	As (ppm)	<10	<10
Ce	<4	<4	<4	<4	Ba	12	740
Co	2	3	3	3	Be	<1	2
Cr	2	24	3	8	Cd	<2	<2
Cu	2	4	2	4	Ce	20	120
La	<2	<2	6	6	Co	10	60
Li	<2	2	<2	<2	Cr	220	500
Mo	<2	<2	<2	<2	Cu	22	48
Nd	<4	<4	<4	<4	Eu	2	4
Ni	<2	15	11	5	Ga	6	20
Sc	<2	<2	<2	<2	La	15	70
Sr	7400	4000	220	380	Li	33	14
V	<2	22	<2	<2	Mo	<2	<2
Zn	3	3	5	2	Nb	11	N/A
					Nd	21	55
					Ni	84	340
					Pb	4	8
					Sc	11	21
					Sr	230	1000
					Th	6	11
					V	43	150
					Y	26	26
					Yb	2	2
					Zn	21	100
Lithology	reefal limestone	bioclastic limestone	reefal limestone	reefal limestone		yellowish-brown mottled highly altered volcaniclastic rock(?), pedogenic	fresh, alkalic basalt

All analyses were performed by U.S. Geological Survey analytical laboratories in Denver, Colorado and Menlo Park, California. Ten major oxides analyzed by wavelength dispersive x-ray fluorescence spectroscopy, Denver and Menlo Park. Analytical expertise provided by J. Taggart, A. Bartel, D. Siems, R. Lerner, B. King, D. Vivit, and M. Dyslin. Minor and trace elements analyzed by inductively coupled plasma atomic emission spectroscopy, Denver. Analytical expertise provided by P. Briggs, and B. Anderson. FeO, CO_2, and water determined by wet chemical methods, Menlo Park. T. Fries, L. Espos, and S. Neil provided analytical expertise.

[1] The presence of organic materials prevented the accurate determination of FeO. Total Fe reported as Fe_2O_3. CO_2 value represents carbonate carbon only. See Table C in Appendix 2 for total carbon content.

N/A not analyzed.

† Totals based on LOI (loss on ignition) at 900 °C.

‡ Value reported is from emission spectroscopy data.

For the four carbonate samples the following elements were analyzed but were below detection limits (in ppm): Ag <2; As <10; Au <8; Be <1; Bi <10; Cd <2; Eu <2; Ga <4; Ho <4; Nb <4; except N/A for 6-16-2605 and 6-19-2934; Pb <4; Sn <10; Ta <40; Th <4; U <100; Y <2; and Yb <1.

For the two volcanic and sediment samples the following elements were analyzed but were below detection limits: Ag <2; Au <8; Bi <10; Ho <4; Sn <10; Ta <40; U <100.

Stable Isotopic Composition of Calcite

The isotopic composition of the calcite-replaced limestone and the sparry calcite cements are essentially the same and average 25.1$^0/_{00}$ $\delta^{18}O$ and -9.8$^0/_{00}$ $\delta^{13}C$ (Table 32). These values are comparable to those of secondary calcite from the other cores and indicate precipitation of calcite in predominantly freshwater with both organic matter and seawater as sources of carbon.

Table 32. Carbon and oxygen isotopic compositions of calcite from Hole 6, Aitutaki, Cook Islands.

Sample No.	$\delta^{13}C$ PDB	$\delta^{18}O$ SMOW	Mineralogy	Sample Description
6-14-2308	-10.9	25.1	Calcite	calcite replaced reefal limestone
6-16-2605	-9.8	25.2	Calcite	sparry calcite layer
6-17-2657	-9.3	25.3	Calcite	sparry calcite layer
6-17-2660	-8.7	25.2	Calcite	sparry calcite layer
6-18-2763	-10.4	24.8	Calcite	sparry calcite layer
Average Calcite	-9.8	25.1		

Analyses performed at U.S. Geological Survey isotope laboratory by Doug White.

Uranium-Series Age Dates

The uranium content is high for the upper limestone beds (Table 33) and excess ^{235}U occurs throughout the limestone section, both above and below the basalt flows. The apparent maximum age (3,000 years) of the limestone at 6.9 m indicates an average vertical reef growth rate of 2.3 m/1,000 years; if a younger age is used, the rate is greater.

Table 33. Uranium and thorium contents and U-series apparent ages of coral from Hole 6, Aitutaki, Cook Islands.

Lab No.	Field No.	U ppm	Th ppm	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	U/Th age 1,000 years	Corrected age 1,000 years	Coral Types and Comments	Mineralogy (XRD)*
660	6-2-693	4.880±0.232	0.385±0.387	1.166±0.052	0.793±1.387	0.018±0.025	$1.9^{+2.9}_{-2.7}$	$0.2^{+2.8}_{-2.6}$	Excess ^{235}U; *Astropora*	A(c)
661	6-18-2160	0.991±0.063	0.050±0.042	1.842±0.703	64.781±54.209	0.807±0.064	$158.9^{+36.0}_{-25.9}$	$157.7^{+35.6}_{-25.8}$	Excess ^{235}U; Recrystallized *Porites*	C
662	6-18-2752	1.027±0.063	0.188±0.188	0.958±0.076	15.41±15.52	0.969±0.144	≥124	—	Excess ^{235}U; Recrystallized *Acropora*	C

*	Major	Moderate	Minor or Trace
Aragonite	A	(A)	(a)
Calcite	C	(C)	(c)

Petrography

Hole 6 Core 1 Depth ~5 m
Mineralogy (XRD): Aragonite; minor calcite, Mg-calcite.
Classification: Unaltered Coral.

This well-preserved faviid coral shows radial arrangement of septa. Acicular radiating aragonitic crystals that compose the skeleton are unaltered. Some botryoidal cement is present in the pores (Plate 22A). High initial growth-framework and intragranular porosity are evident.

Hole 6 Core 3 Depth ~7.75 m
Mineralogy (XRD): Calcite, aragonite, Mg-calcite.
Classification: *Halimeda* Packstone, Biomicrite.

Halimeda algae plates are the primary bioclast in this grain-supported biomicrite. Other bioclasts include gastropods, foraminifera (nummulites and other benthics), bivalve and echinoderm fragments. Well-preserved burrows are partly infilled with detrital bioclasts and micrite. Gastropod shell crystals of aragonite are relatively unaltered. Bioclasts are cemented in detrital micrite that contains some dark organic material. Interparticle pore spaces also contain large neomorphically formed spar. Large, equant calcite cement grains of freshwater phreatic origin infill a few molds. Some clasts were partly dissolved leaving secondary intraparticle pores. Porosity is high with intraparticle > interparticle, vuggy.

Hole 6 Core 3 Depth ~7.75 m
Mineralogy (XRD): Major Mg-calcite, aragonite; moderate calcite.
Classification: *Halimeda* Packstone, Biomicrite.

Halimeda plates compose 85 to 90% of the clasts. Burrows, bivalve fragments, foraminifera, echinoderms, and a few clasts of red algae are also present. The bioclasts float in a micritic matrix that underwent neomorphism to calcite in a few places. *Halimeda* grains partly neomorphosed to equant calcite crystals. This neomorphic calcite is the dominant cement; little void-filling cement developed. Large vugs within the micritic matrix crosscut some grains attesting to a period of non-fabric-specific dissolution. Porosity is high with vuggy >> moldic.

Hole 6 Core 6 Depth ~12.4 m
Mineralogy (XRD): Calcite.
Classification: Recrystallized Wackestone, Sparse Biomicrite.

This sample contains large (up to 1 cm) echinoid spines floating in a bioclast-rich micritic matrix (Plate 22B). Red algae, foraminifera, and rare gastropod shell fragments are also present. Several cement types are evident. Neomorphic calcite is interspersed with patches of fine-grained micrite and is commonly superimposed on void-filling crystals. Large, euhedral calcite crystals, indicative of freshwater phreatic void-filling cement, line some vugs. Much cement was dissolved leaving intercrystal pores spaces. In places, the void-filling cement recrystallized to secondary calcite or partly dissolved. Porosity is variable and low with intercrystal > micropore, vuggy.

Hole 6 Core 9 Depth ~17 m
Mineralogy (XRD): Calcite; minor kaolinite, goethite.
Classification: Altered Volcanic Ash and Crystalline Calcite.

Large calcite crystals show crystal growth horizons marked by faint lines of altered material that was probably originally volcanic ash. Some poikilotopic crystals are also present that probably formed in a freshwater phreatic environment. Partial dissolution of crystals (Plate 23A) and extensive fracturing is evident. Fracture and intercrystalline porosity is moderate to low.

Hole 6 Core 12 Depth 20.5 m
Mineralogy (XRD): Major pyroxene; moderate plagioclase, K-feldspar, olivine, smectite; minor kaolinite, amphibole.
Classification: Alkali Olivine Basalt.

Phenocrysts of olivine occur in a groundmass of small pyroxene crystals, plagioclase laths, K-feldspar and clay minerals. Some leaching, deposition of hydrous iron oxides, and alteration to clay minerals occurred. A few voids were lined with hydrous minerals and infilled with void-filling sparry calcite. This basalt probably erupted in a submarine environment and is very similar to the flows from Hole 3.

Hole 6 Core 13 Depth ~21.5 m
Mineralogy (XRD): Calcite.
Classification: Recrystallized Boundstone, Biolithite.

Faint micritic envelopes outline meandering pores suggesting coral is the main bioclast. A few clasts of encrusting foraminifera, encrusting bryozoa, and borings are also identifiable. The majority of the cement has wavy crystal boundaries characteristic of neomorphic calcite. Microspar is commonly present between many of the larger neomorphic crystals. Large euhedral crystals with straight boundaries indicative of freshwater phreatic cement infill voids. Some of these void-filling calcite cement crystals neomorphosed and partly dissolved. Fractures crosscut cements indicating that fracturing postdated cementation. Geopetal fabrics are present in borings. Porosity is moderate with intercrystal > vuggy > fracture.

Hole 6 Core 16 Depth 26 m
Mineralogy (XRD): Calcite.
Classification: Recrystallized Boundstone, recrystallized Biolithite.

Algal encrusted recrystallized coral occurs, but sparry and druzy calcite cement of various grain sizes, origins, and generations make up 70% to 80% of this rock. Neomorphism is extensive. Some large crystals show a habit characteristic of void-filling, freshwater phreatic precipitation that, in places, underwent secondary neomorphic alteration. At least two periods of dissolution are evident. The probable sequence of diagenetic events is dissolution, void-filling cementation, neomorphism, and further dissolution. Total and partial dissolution of cement crystals gave rise to moderate vuggy and intercrystal porosity.

Hole 6 Core 19 Depth 29.34 m
Mineralogy (XRD): Calcite.
Classification: Recrystallized Boundstone, recrystallized Biolithite.

Three textures occur: 1) recrystallized coral, 2) bioclasts (including abundant red algae and nummulite foraminifera, coral fragments, bryozoans, and gastropods molds) cemented by void-filling marine phreatic cement, and 3) bioclasts (including algae, coral fragments, and bivalves) in a micritic matrix. Detrital micrite infilled many framework pores producing geopetal textures. Several generations of cement occur. Some void-filling cement crystals inverted to calcite. Micrite inverted to sparry calcite. Fractures that crosscut cement crystals are infilled by a later generation of void-filling calcite cement. A complex diagenetic history of deposition, dissolution, void filling, neomorphism, fracturing, void filling, and further neomorphism is apparent. Porosity is moderate and variable with moldic > vuggy.

Summary of Hole 6

Hole 6 consists of an upper limestone unit interbedded with carbonate sand, 0 to 14 m; a middle volcanogenic unit divided into an upper pedogenic section cemented and veined by calcite and a lower basalt, 14 to 21 m; and a lower recrystallized limestone unit with abundant sparry calcite layers, 21 m to 30 m.

In the upper limestone section, the predominant bioclasts are *Halimeda* algae and coral, with minor amounts of mollusk, foraminifera, and echinoderm fragments (Table 34). This assemblage is typical of a sandy lagoonal biofacies. The lower limestone section contains abundant coral, algae, bryozoa, and foraminifera, suggesting a lagoon coral mound facies.

The upper 9 m of section is composed of aragonite with botryoidal aragonite cement and high primary growth-framework and intergranular porosity. It is unknown why Mg-calcite occurs exclusively in this upper section of Hole 6 and not in any other places drilled. The average vertical growth rate of coral in this section was at least 2.3 m/1,000 years. Below the aragonite zone down to the basalt, minor to moderate neomorphism of calcite occurred and moderate freshwater phreatic void-filling cement formed. Neomorphism dominated diagenesis below the basalt where pore waters were more restricted. Moderate porosity results from intercrystalline pores and secondary dissolution. Abundant sparry calcite layers and the calcite-replaced limestone formed in a freshwater environment.

The alkali olivine basalt erupted in a submarine environment and is petrographically and chemically similar to the flow sampled at Hole 3 and, in fact, they may be the same flow. The basalt was deeply weathered in a subaerial environment and the weathering products were cemented by calcite precipitated in a freshwater environment.

Table 34. Summary of petrography, Hole 6.

Geology

Depth (m)	Mineralogy	Major Diagenetic Fabrics	Minor Diagenetic Fabrics	Major Porosity Types	Minor Porosity Types	Degree of Porosity
5	A>>C	—	B	GF	I	A
7.75 I	C,A,M	VF/fp	N	I	i,V	A
7.75 II	M,A>C	N	—	V	M	A
12.4	C	VF/fp,N	—	X	V	m
17.1	C>>I,K	Pk	VF/fp	F	X	M-m
20.5	S>K	VF	—	—	—	—
21.6	C	N	VF/fp	X	V,F	M
26	C	N	VF/fp	V	X	M
29.34	C	N,VF	—	M	V	M

Biology

Depth (m)	Coral	Algae	Mollusks	Echinoderms	Bryozoa	Foraminifera
5	*	—	—	—	—	—
7.75 I	—	*	X	X	—	X
7.75 II	—	*	X	X	—	X
12.4	—	*	X	*	—	*
21.6	*	—	—	—	*	*
26	*	*	—	—	—	*
29.34	*	*	*	—	X	*

Key to Table 34

Mineralogy:
- C: Calcite
- A: Aragonite
- M: Mg-calcite
- S: Silicates
- K: Clay minerals
- I: Iron minerals

Cements: Type/Origin

Type:
- VF: void-filling sparry calcite
- N: neomorphically derived sparry calcite
- Pk: poikilotopic overgrowth
- B: Botryoidal

Origin:
- fp: freshwater phreatic

Porosity: Degree/Development

Development:
- M: moldic
- GF: growth framework
- V: vuggy
- I: intraparticle
- F: fracture
- X: intercrystal

Degree:
- Abundant porosity: A
- Moderate porosity: M
- Minor porosity: m

Biota:
- * abundant
- X present
- — absent

SUMMARY AND CONCLUSIONS

Carbonate Sections

A great deal of lithological and mineralogical diversity exists within the drilled stratigraphic sections of Aitutaki almost-Atoll. The carbonate sections consist of an upper section of aragonite ±calcite limestone and sediment. The aragonite section is 6 m to 10 m thick in five of the six stratigraphic sections; at Hole 5, where a depression is partly filled with nearly 20 m of carbonate sediment, the aragonite persists down to 20 m. The aragonite deposits are relatively chemically pure containing more strontium and, in some deposits, more magnesium than the calcite limestones. Fossils in aragonite limestone are predominantly corals. Minor incipient cementation by acicular void-filling aragonite occurred, indicating a marine phreatic environment with good pore water circulation.

Below the aragonite deposits occurs a transitional section 3 m to 7 m thick where aragonite is subordinate to calcite. This section ends by 11 m to 16 m subbottom depth. Calcite has not completely replaced the aragonite in this transition zone and strontium values are intermediate between those of aragonite and calcite limestones. Diagenesis took place in a freshwater and mixed phreatic environment with good to poor circulation. The age of this transition zone is not known, but it probably represents a solution unconformity produced during the last glacial maximum at around 18,000 years ago (Fig. 8). Deposits above this transition zone formed during the Holocene transgression or when sea level reached its present position 4,000 to 6,000 years ago. Contradictions exist among some of the U-series apparent ages, the rocks stratigraphic position relative to present sea level, and generally accepted models of sea level positions during the last 20,000 years (Fig. 8). Apparent ages of some corals are far too old for their stratigraphic position and would require coral growth when sea level was tens to many tens of meters below their apparent growth position. This can be reconciled by (1) rapid tectonic uplift at nearly the same rate as the rise of sea level, which would have to have abruptly ceased in middle Holocene time, or (2) by contamination of the limestones by older volcanic detritus. The latter, explanation is preferred.

The calcite limestone sections begin at 10 m to 16 m (20 m for Hole 5) subbottom depths. These limestones also contain little contamination, even though they developed adjacent to a volcanic island. Little volcanic detritus was incorporated into the growing reefs. Primary and secondary neomorphism of grains and cements characterize the calcite limestone sections. Diagenesis took place in a freshwater phreatic environment. The common occurrence of interlocking crystals of equant calcite that coarsen towards pore centers is typical of cementation within a system of actively flowing pore waters, whereas fabric specific neomorphism occurs where pore waters are restricted or stagnant (Longman, 1980). Good examples of these two systems are found in Holes 2 and 6. In the lower part of Hole 6, neomorphism is pervasive where limestone is capped by basalt and pore water circulation was restricted. In contrast, Hole 2, which is the only hole that lacks basalt and mud deposits, contains the most abundant, well-developed freshwater void-filling calcite cement.

The calcite limestone is replaced by dolomite at 40 m subbottom depth in Hole 2 and contains some dolomite below 47 m in Hole 5. Dolomitization overprinted earlier neomorphically derived grains and cement. The diagenesis was in a zone of mixed freshwater and seawater with good circulation.

All the limestone sections below the aragonite-calcite transition zone contain thick (up to 10 cm) bedding parallel sparry calcite layers. These calcite layers formed in a freshwater environment and filled solution cavities or fractures in the limestones. Calcite crystals are as much as 4 cm long.

The oldest U-series age is about 200,000 years, determined from a sample of dolomite from Hole 2 at 41.5 m subbottom depth. This and some of the other apparent ages of limestone have undoubtedly been affected by diagenesis as aragonite transformed into calcite and calcite into dolomite. Depending on the number of solution unconformities in the sections, the oldest limestones drilled are likely between 100,000 and 200,000 years old.

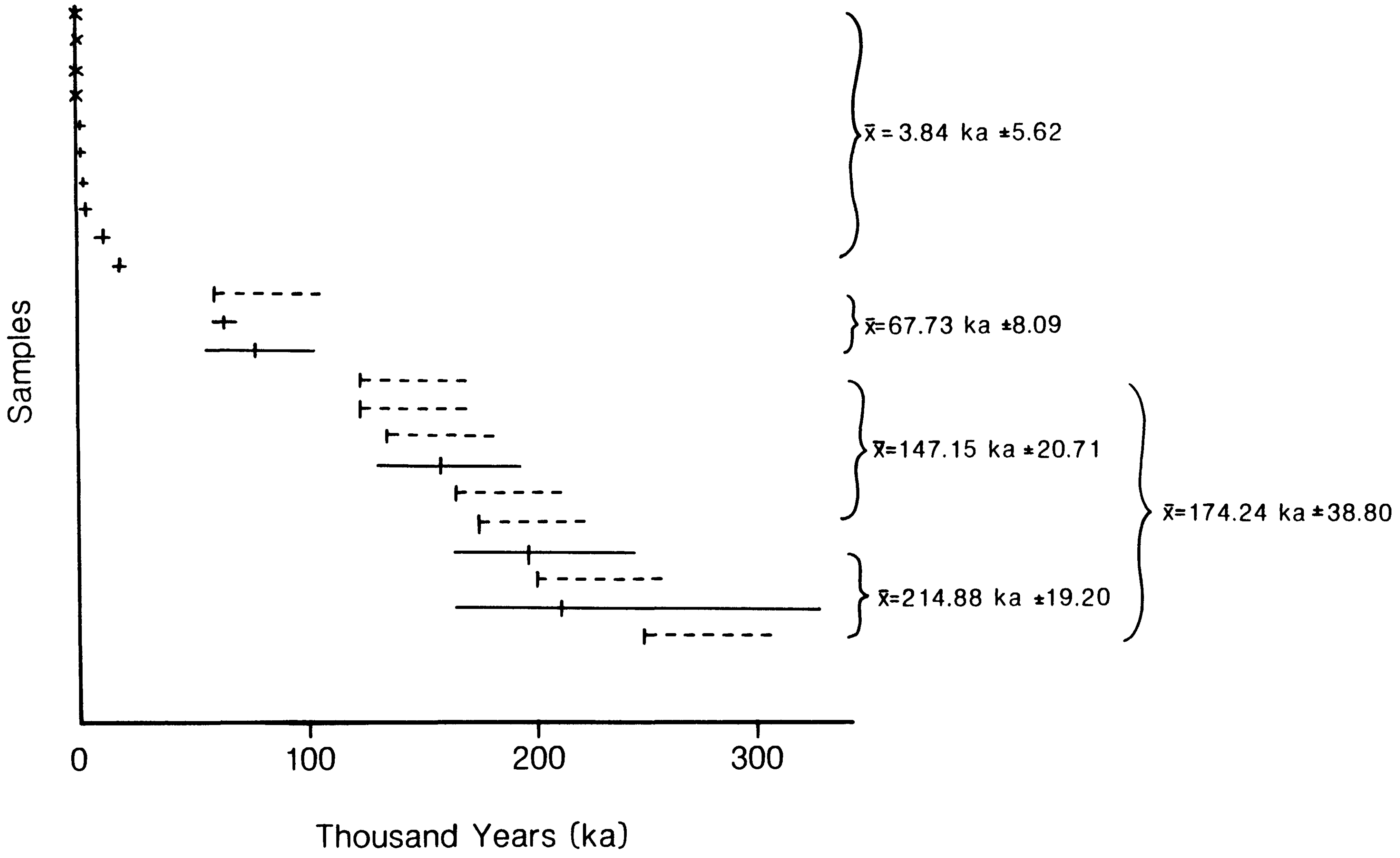

Figure 8. Plot of samples versus age for all samples with uranium-series apparent ages. Ages to the right are average ages and standard deviations for samples of possible distinct age groups.

The isotopic compositions of the carbonates indicate that the primary biogenic aragonite precipitated from seawater and the secondary calcite precipitated from freshwater (Fig. 9; Appendix 3). A freshwater origin is indicated for both the sparry calcite cement and the calcite that replaced the aragonitic limestones. The regional $\delta^{18}O$ of meteoric water for the Pacific at 18° south latitude is about -4 to $-5^0/_{00}$ (Yurtesever, 1975) and seawater is $0^0/_{00}$; the calculated δD of meteoric water with $\delta^{18}O$ of $-5^0/_{00}$ ($\delta D = 8\ \delta^{18}O + 10$) is $-50^0/_{00}$ (Craig, 1961). This clearly shows that secondary calcite from Aitutaki with an average $\delta^{18}O$ of $25.1^0/_{00}$ ($-5.59^0/_{00}$ PDB) and δD of $-50^0/_{00}$ precipitated from meteoric water; deposits were never deeply buried and temperatures remained relatively low. Dolomite from Aitutaki with an average $\delta^{18}O$ of $31.1^0/_{00}$ ($+0.23^0/_{00}$ PDB) and δD of $-27^0/_{00}$ formed in a zone of mixed freshwater and seawater, with roughly equal amounts of each. The origin of dolomite in a zone of mixing (reflux model) is consistent with many other studies of the dolomitization of atoll limestones (for example Aissaoui and others, 1986). Without pore water chemical data, it is difficult to equate the mechanism of dolomitization with chemical changes in the system. Certainly, the high porosity and flushing of large amounts of fluids through the reef aided in the pervasive dolomitization at Aitutaki.

We suggest the following sequence of large-scale events. The aragonitic limestone sections were replaced by calcite and the numerous sparry calcite layers formed during a major low-stand of sea level. The very pure low-magnesium calcites precipitated predominantly from freshwater. The carbon was derived from the degradation of organic matter, perhaps by bacterial metabolic activity, and from bicarbonate in seawater via the dissolution of reefal debris that originally formed in seawater. At this same time, solution cavities and karst development occurred as the limestones were exposed to the subaerial environment as the result of lowered sea level. During the last major sea level low, the present lagoon stood about 100 m above sea level. A large freshwater lens developed that produced void-filling cement; neomorphism extensively altered earlier-formed diagenetic carbonates. Dissolution vugs, characteristic of the limestones, formed in the upper part of the lens where there was good exchange with atmospheric carbon dioxide and a high rate of water flow. Pervasive dolomitization occurred as sea level rose and an extensive mixing zone of freshwater and seawater formed; large quantities of fluids flushed through the porous calcite limestone (Fig. 9). The dolomitization front moved upsection as sea level rose, which is now at 40 m subbottom depth. A minimum of 30 m of limestone were pervasively dolomitized. It is not known whether dolomitization is still active at the 40 m boundary. Alternatively, dolomitization of the entire 30+ m section may have occurred during a single still-stand of sea level, when sea level was about 40 m lower than its present level. Where basalt flows inhibited the free circulation of seawater, dolomitization was minor (Hole 5). Dolomite replaced not only the calcite limestone but also freshwater calcite cements that formed during the low-stand of sea level.

Volcanogenic Sections

Volcanogenic deposits include basalt flows, pyroclastic and volcaniclastic deposits, hydrothermal iron hydroxide deposits, and soils formed by leaching and weathering of these deposits. The amount of volcanic material varies from hole to hole. Hole 3 cores are predominantly volcanogenic whereas Hole 2 cores contain little volcanic debris.

Basalt flows include alkalic basalts of several varieties, most commonly alkali olivine basalt and nephelinite. Many separate flow units were recovered that ranged from highly vesicular to massive and fresh to strongly altered. Flows from Holes 1 and 5 are alkali olivine basalts and were probably erupted in a subaerial environment. Flows from Hole 4 are submarine eruptions of nephelinite, and flows from Holes 3 and 6 are submarine eruptions of alkali olivine basalt. The flows from Holes 3 and 6 are probably from the same eruption as based on identical petrographic and chemical compositions. It was commonly difficult to distinguish whether a highly altered volcanic rock was originally a flow, a pyroclastic deposit, or a volcaniclastic deposit. Intense leaching produced a deposit that texturally appeared to be a basalt, but was soft (mud) and

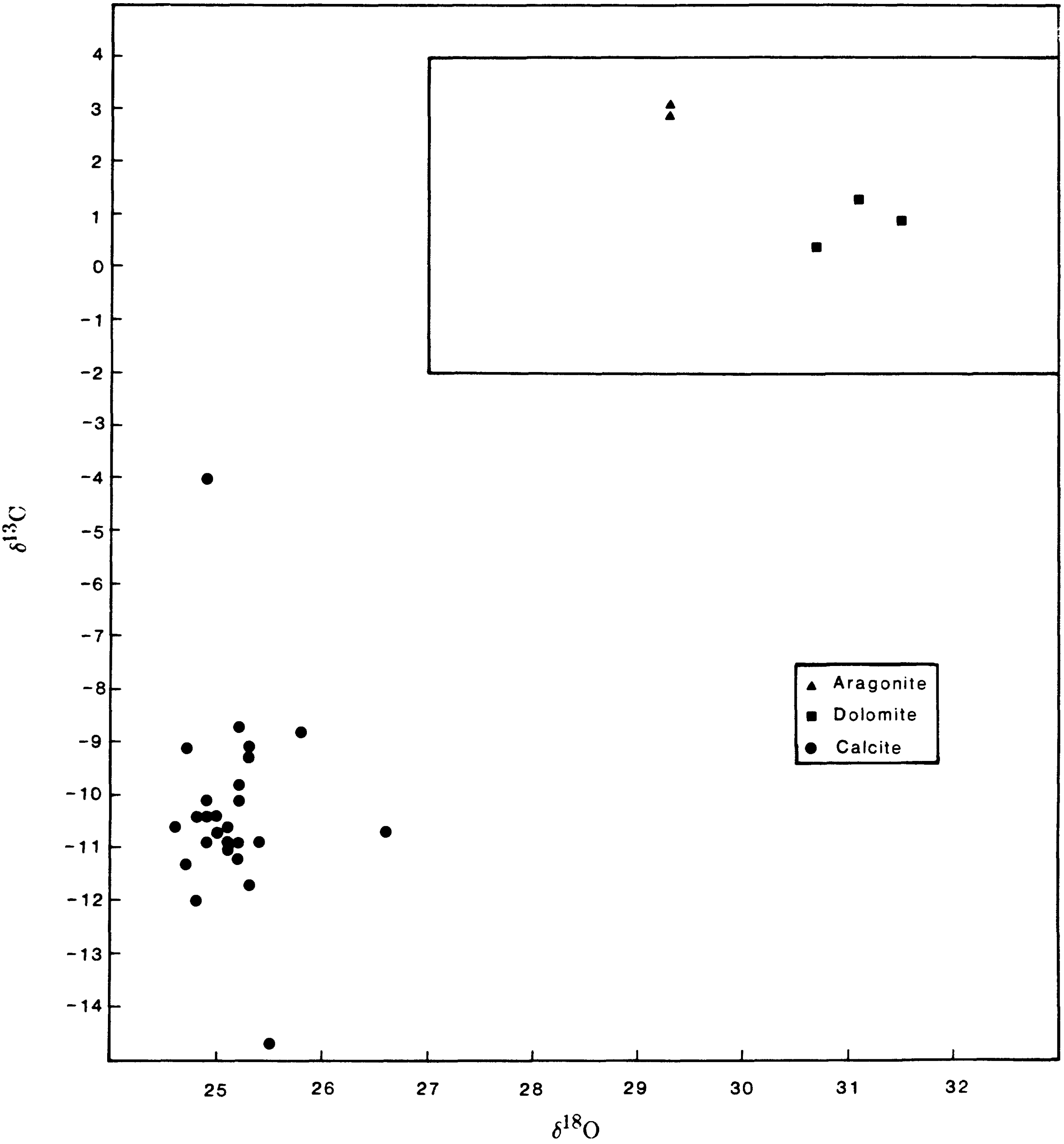

Figure 9. Plot of $\delta^{13}C$ (PDB) versus $\delta^{18}O$ (SMOW) for carbonates from Aitutaki drill cores. The box that encloses the aragonite and dolomite values represents the range of marine biogenic calcite and recent biogenic carbonate sediments.

contained no primary volcanic minerals other than magnetite. Magnetite usually survived the most intense leaching. Some flows were laced with calcite veins and vesicles were filled with calcite. Less commonly vesicles were filled with zeolites (Hole 4) or smectite (Hole 3).

The ages of the basalt flows are unknown, but may be less than 200,000 years, especially those interbedded with the limestones in Holes 5 and 6, and the hydrothermal deposits in Hole 2. The youngest flows dated previously are 660,000 years old as discussed in the introduction. K-Ar dating is in progress on several of the basalt cores.

Volcanogenic sediments include predominantly mud and silty mud formed by subaerial leaching and weathering of basaltic rocks. This soil-forming process occurred *in situ* under tropical to subtropical conditions and produced deposits up to 22 m thick. In places, volcaniclastic rocks may have been deposited, but because of the strong alteration it is virtually impossible to tell if any of the silts and muds were transported. Moderate to intense leaching produced aluminum- and iron-rich deposits composed of kaolinite, goethite, and magnetite with or without smectite and lepidocrocite. Besides these minerals, nordstrandite and anatase occur in soils found in limestone solution cavities and caves that were produced during karst development. Refractory elements were concentrated more by more intense and/or prolonged leaching. Leaching of basalt removed silicon, magnesium, calcium, sodium, and potassium and concentrated aluminum, iron, titanium, phosphorus, chromium, nickel, thorium, uranium, and in places barium, strontium, manganese, arsenic, cobalt, vanadium, and lithium. The highest concentrations of phosphorus encountered occur in these muds. Several elements such as titanium, chromium, lithium, strontium, thorium, and vanadium, decrease from top of the mud sections into the basalts, reflecting the *in situ* leaching and weathering of the basalt flows during soil formation and increasing maturity of the deposits.

Iron hydroxide deposits in Hole 2 cores form thin layers and mottled yellow, reddish, and brown zones in the cores. Iron is the only element enriched in the host dolomites. We suggest that these deposits represent iron oxyhydroxides deposited at the coral-seawater interface by submarine volcanic activity. The mottled core sections (Plate 3B) represent iron oxyhydroxides that were deposited on and in a vuggy limestone that was extensively bored. Much of the limestone void space was filled with these oxyhydroxides, which were later partly replaced by dolomite. Through diagenesis, the oxyhydroxides transformed into very fine-grained iron hydroxides, lepidocrocite and goethite.

Swamp Deposit

A greenish-black mud recovered from Hole 5 represents a swamp deposit composed of organic matter and pyrite with minor amounts of evaporite minerals. The environment of deposition was a stagnant pond probably floored by algal mats, which also accumulated some terrigenous organic matter. Pyrite formed from iron derived from leaching of volcanic rocks or from hydrothermal activity and from sulfur derived from reduction of seawater sulfate. The pond was probably periodically replenished by seawater, but the hydrological system was dominated by evaporation, concentration of brine and minor evaporite formation. Similar ponds occur now on Motu Ee (Fig. 1) and Aitutaki Island.

Resource Considerations

It is clear from the six holes drilled in Aitutaki lagoon that no extensive phosphorite deposits occur. In fact, the highest concentration of P_2O_5 encountered was just under 3%. Small, or stratigraphically deeper, deposits may occur, but they would not be of economic interest.

Leaching of basalt produced high concentrations of several strategically and economically important metals including aluminum (to 25% Al_2O_3), iron (to 31% Fe_2O_3), titanium (to 5.14% TiO_2), chromium (to 0.2%), nickel (to 0.1%), manganese (to 2.0% MnO), uranium (to 14 ppm), and thorium (to 49 ppm); smaller enrichments of cobalt, vanadium, lithium, arsenic, and other metals occur. These maximum metal concentrations are enriched 1.6, 4.0, 6, 20, 13, 15.5, 5, and 6 times over their crustal average, respectively. The enrichment of chromium is especially high. The source of chromium, titanium, and nickel is magnetite, titanaugite, and ultramafic xenoliths in the basalt.

Even though these metalliferous muds are not of immediate economic interest, the metal enrichments are significant and warrant further studies. Weathering of mafic and ultramafic volcanic rocks has produced economic ore deposits in, for example, New Caledonia, where nickel laterites are mined. However, these laterites are higher grade and larger tonnage deposits than those in Aitutaki.

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PLATES

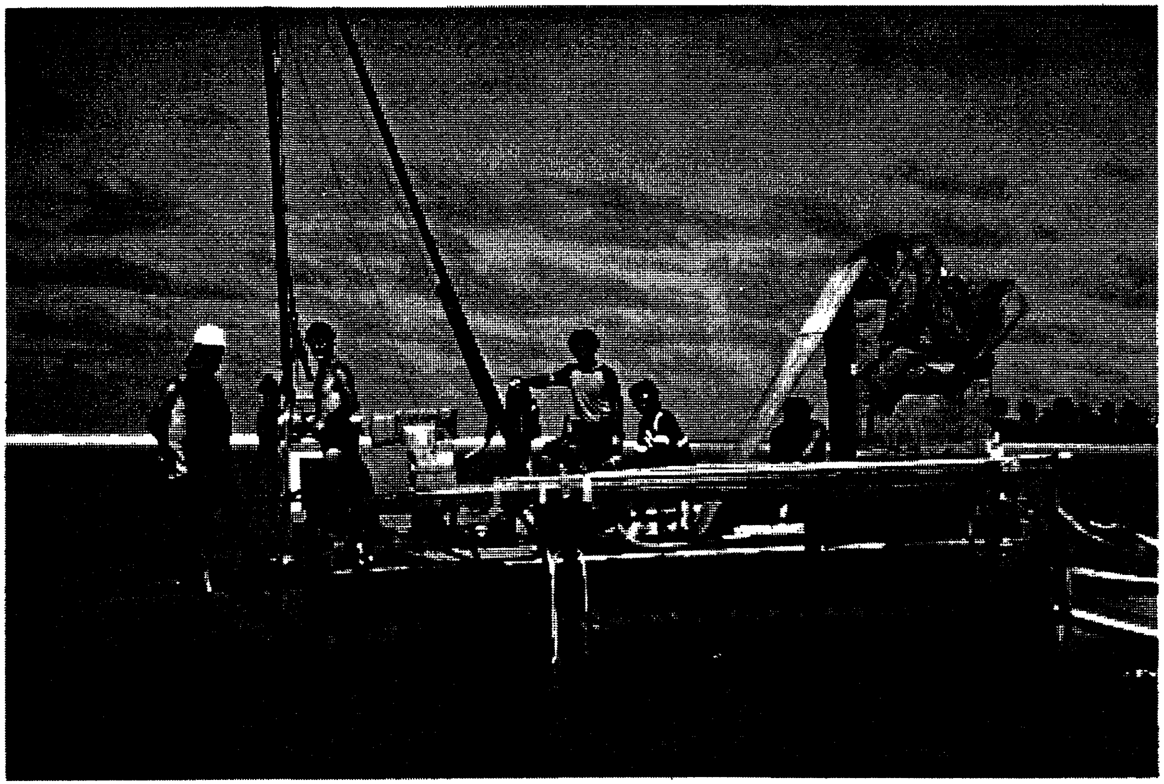


PLATE 1

Portable floating drill rig and platform used to drill six holes in Aitutaki lagoon to a maximum depth of 70 m.

PLATE 2

Drill cores from Aitutaki lagoon:

A: Reefal limestone: top Hole 2, Core 1, ~17-42 cm; bottom, Hole 4, Core 3, ~150-180 cm.

B: Reefal limestone and sparry calcite crystals to 3 cm long from near the bottom of Core 16, Hole 2, at 2360 cm subbottom depth.


A

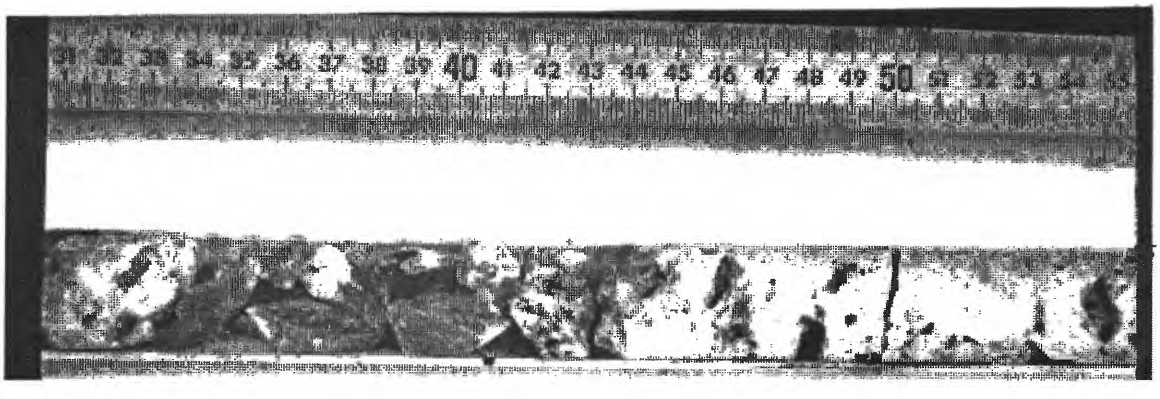
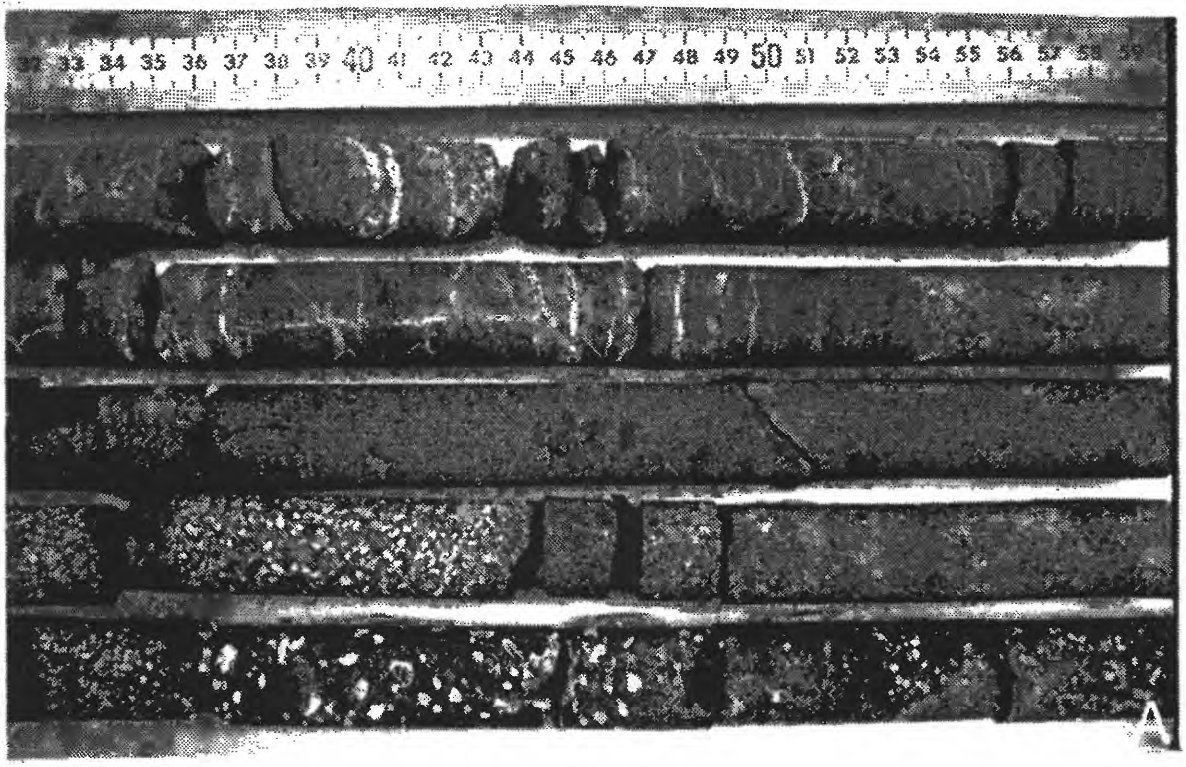


PLATE 3

Drill cores from Aitutaki lagoon:

A: Alkalic basalt cores, from top to bottom: Hole 1A, Core 27, ~3585-3615 cm, note calcite veins and xenoliths at 43 cm mark; Hole 1A, core 28, ~3670-3700 cm, note calcite veins and xenoliths at 54-55 and 57-58 cm marks; Hole 3, Core 26, ~3880-3910 cm; Hole 4A, Core 19, ~2860-2890 cm, zeolites fill vesicles in this nephelinite; Hole 4A, Core 20, ~2980-3010 cm, zeolites fill the vesicles.

B: Brown and gray mottled dolostone from Hole 2: From top to bottom core 43, ~6260-6290 cm; Core 44, ~6310-6340 cm; Core 44, ~6400-6430 cm; Core 45, ~6480-6510 cm; Core 45, ~6570-6600 cm. Brown mottling is probably the result of deposition of iron oxyhydroxides from submarine hydrothermal discharges.


32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59
A


40
50
B

Hole 1A

Depth 10.85 m

PLATE 4A

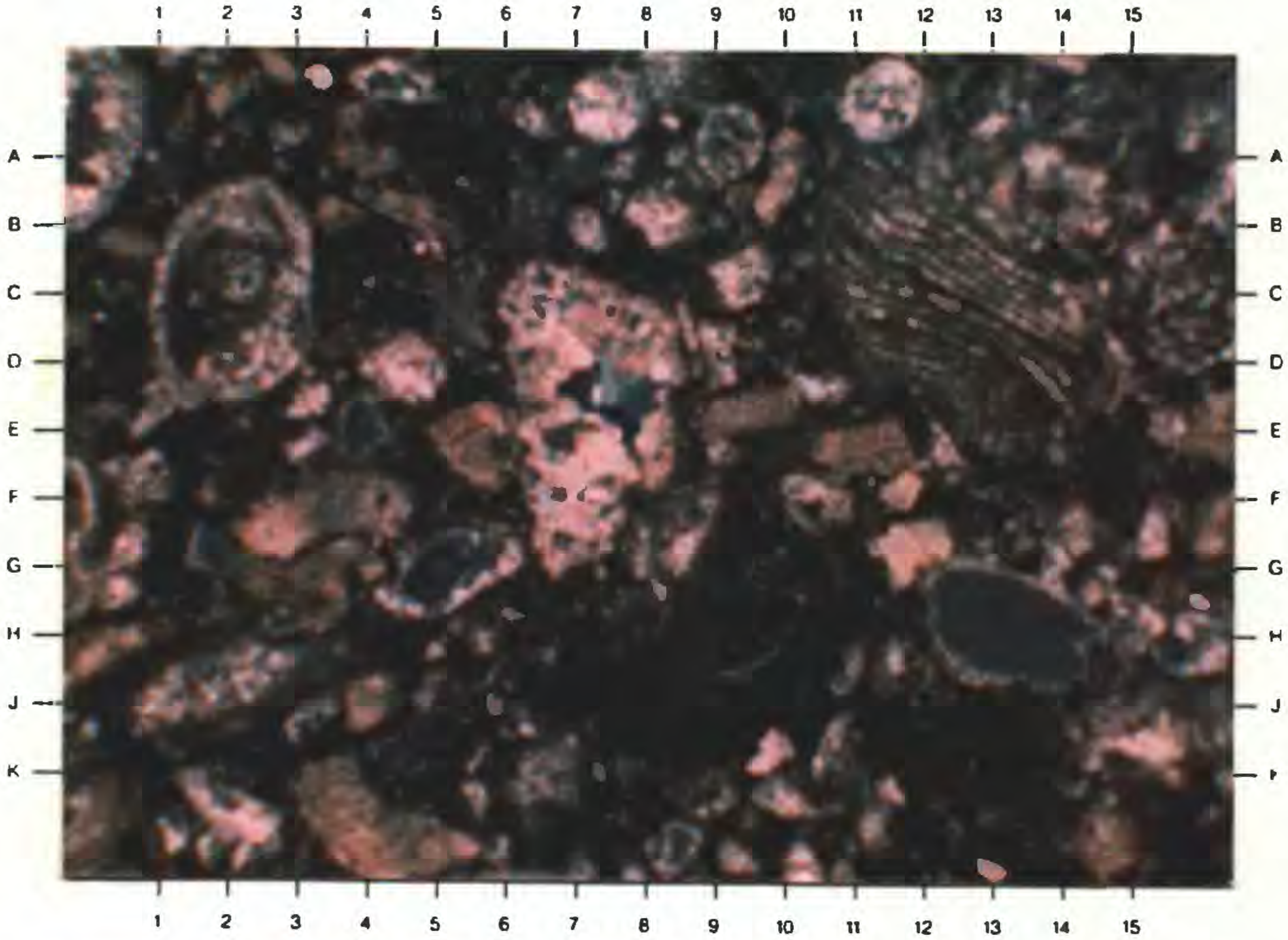
Overview of a bioclastic packstone, biomicrite. A variety of skeletal grains show varying degrees of preservation ranging from unaltered fragments, e.g., bivalve (C-2); neomorphism, e.g., red algal fragment (D-13); dissolution (H-13); and void-filling sparry cement (E-8). Partially crossed nicols, distance across photograph: 2.3 mm.

Hole 1A

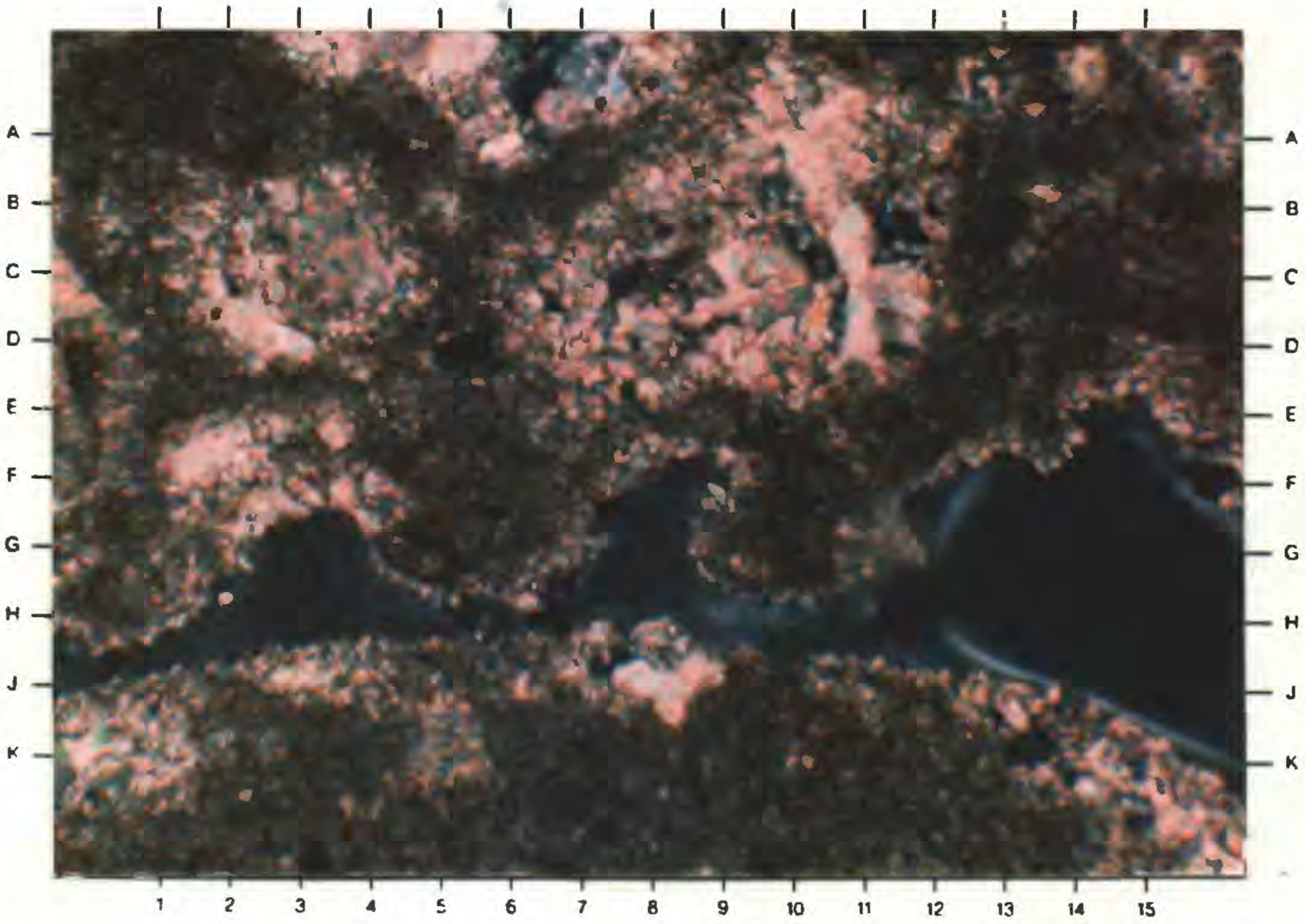
Depth 10.85 m

PLATE 4B

Bivalve mold within a partially neomorphosed micritic matrix. The outline of the bivalve showing the ornamentation of the shell's exterior has been retained. At C-8 a section of the micritic matrix has been neomorphosed to sparry calcite. Partially crossed nicols, distance across photograph: 0.56 mm.


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
A B C D E F G H J K

A


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
A B C D E F G H J K

B

Hole 1A Depth 15.30 m

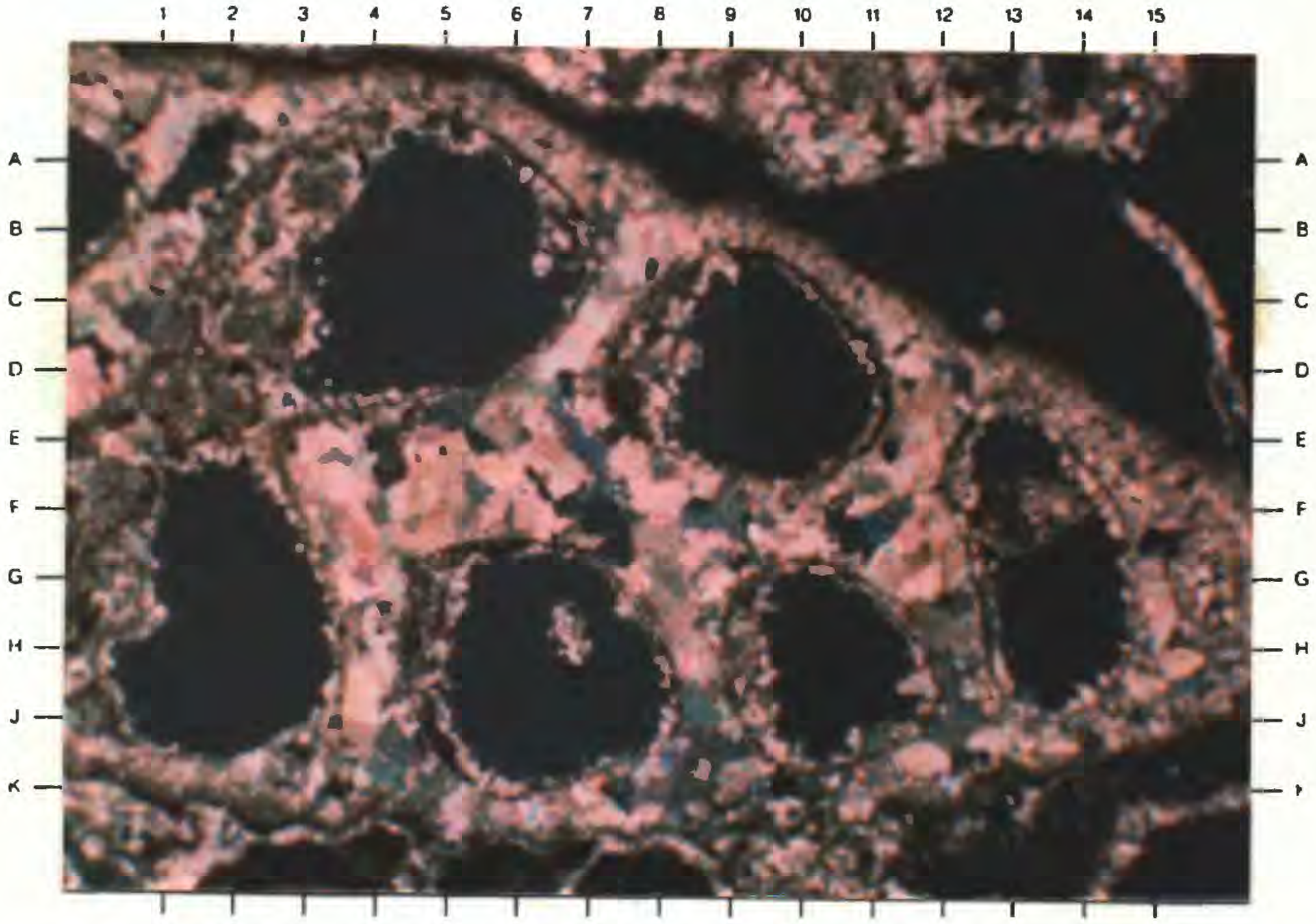
PLATE 5A

Neomorphosed gastropod within a micritic matrix. The original boundary of the inner chamber is marked by micritization. An early episode of cementation lines the chamber wall. Partially crossed nicols, distance across photograph: 2.3 mm.

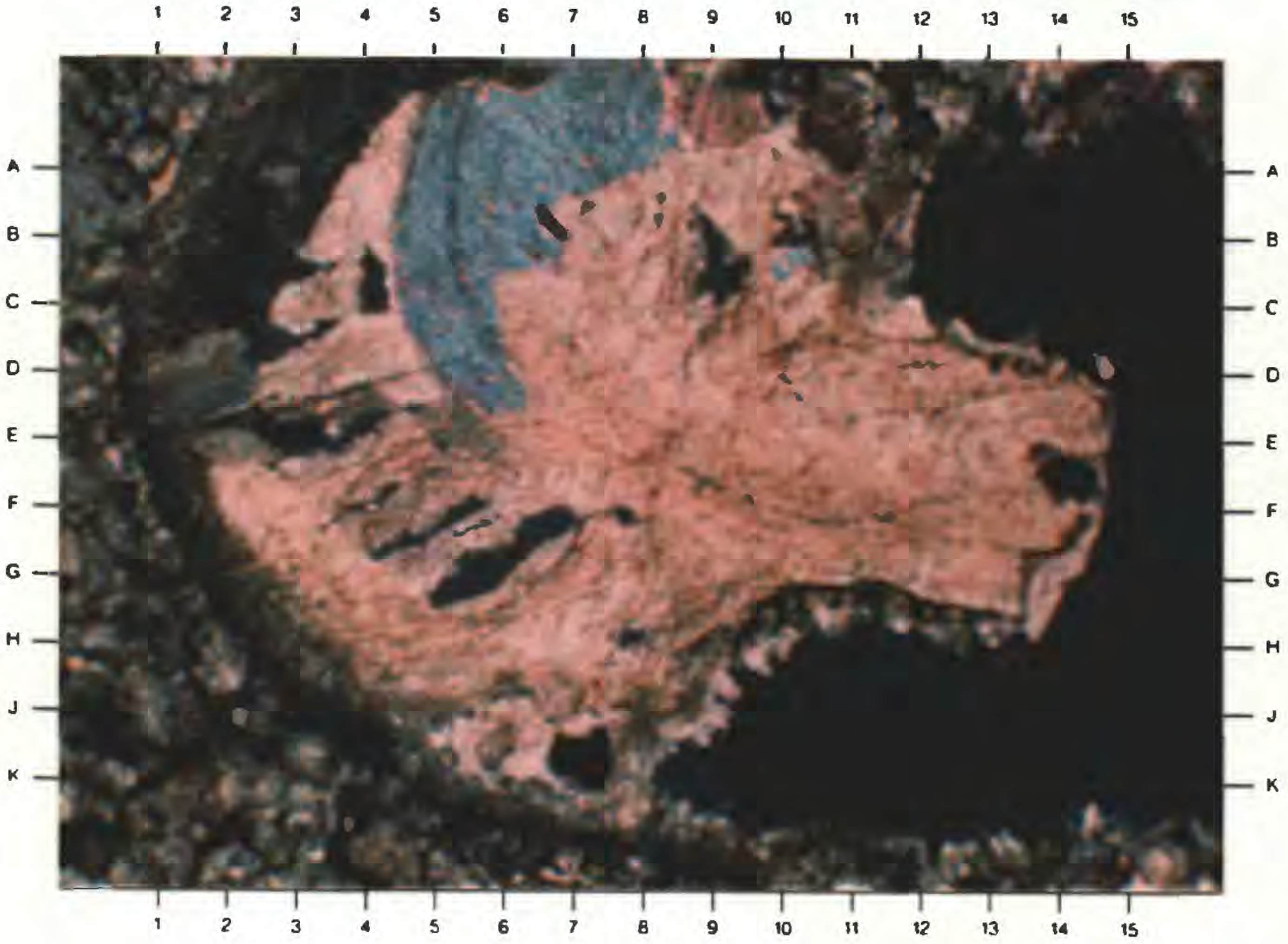
Hole 1A Depth 19.60 m

PLATE 5B

Bivalve fragment in a recrystallized matrix. Micritization of the outer shell wall was followed by early neomorphism (B-6). An episode of dissolution (G-6 and J-12) was followed by void-filling sparry calcite (H-9). Partially crossed nicols, distance across photograph: 2.3 mm.


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
A B C D E F G H J K

A

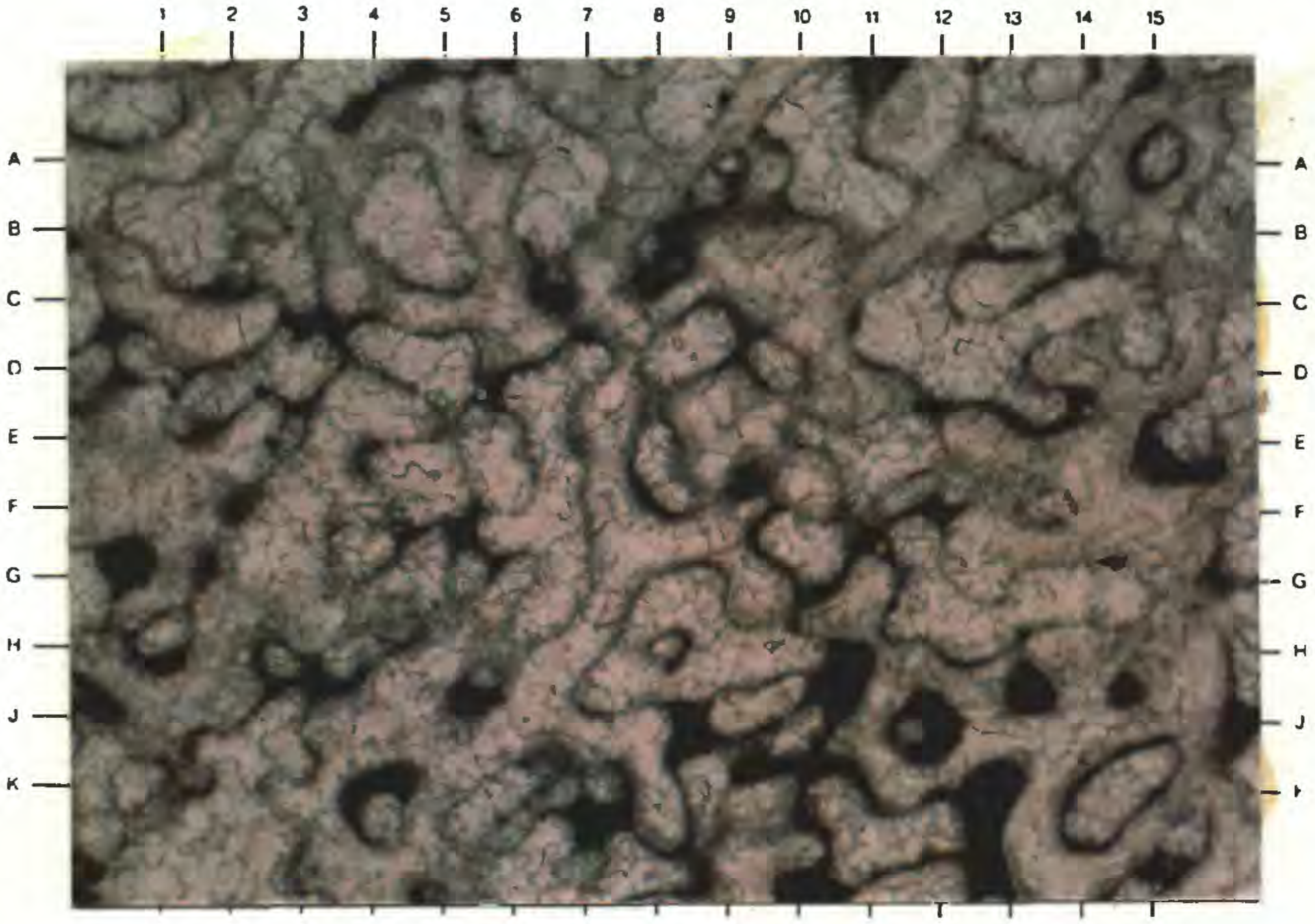

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
A B C D E F G H J K

B

Hole 1A Depth 27.65 m

PLATES 6A,B

Coral skeleton altered to calcite. Two phases of diagenesis are seen in the coral. The skeleton was neomorphosed and sparry calcite infills the primary pore space. The skeletal outline is marked by a micritic rim. Detrital micrite partly fills some of the pores and predates the sparry calcite (A-4). 6A plane-polarized light and 6B same view under crossed nicols. Distance across photograph: 2.3 mm.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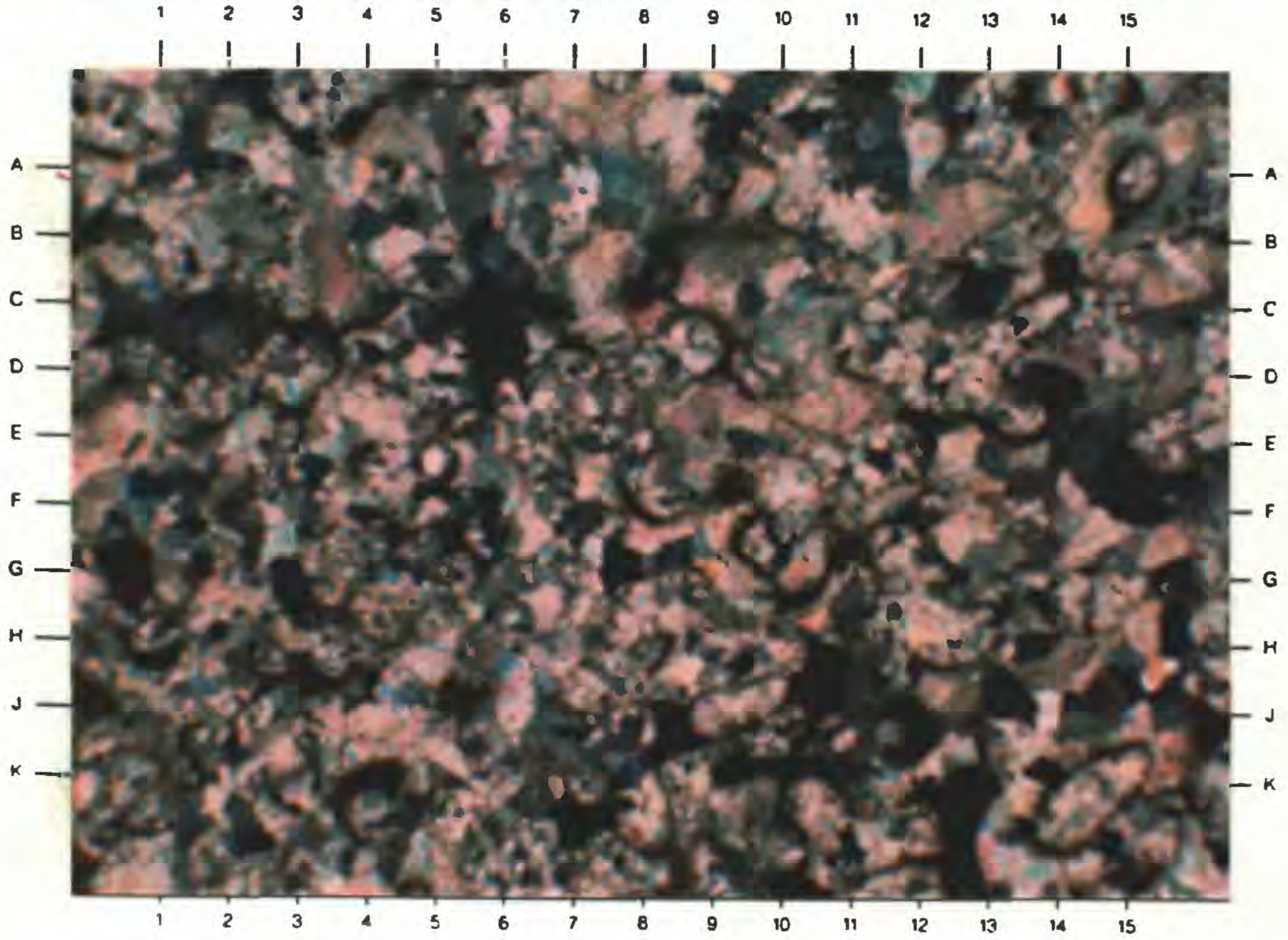
A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B

Hole 2 Depth 0.32 m

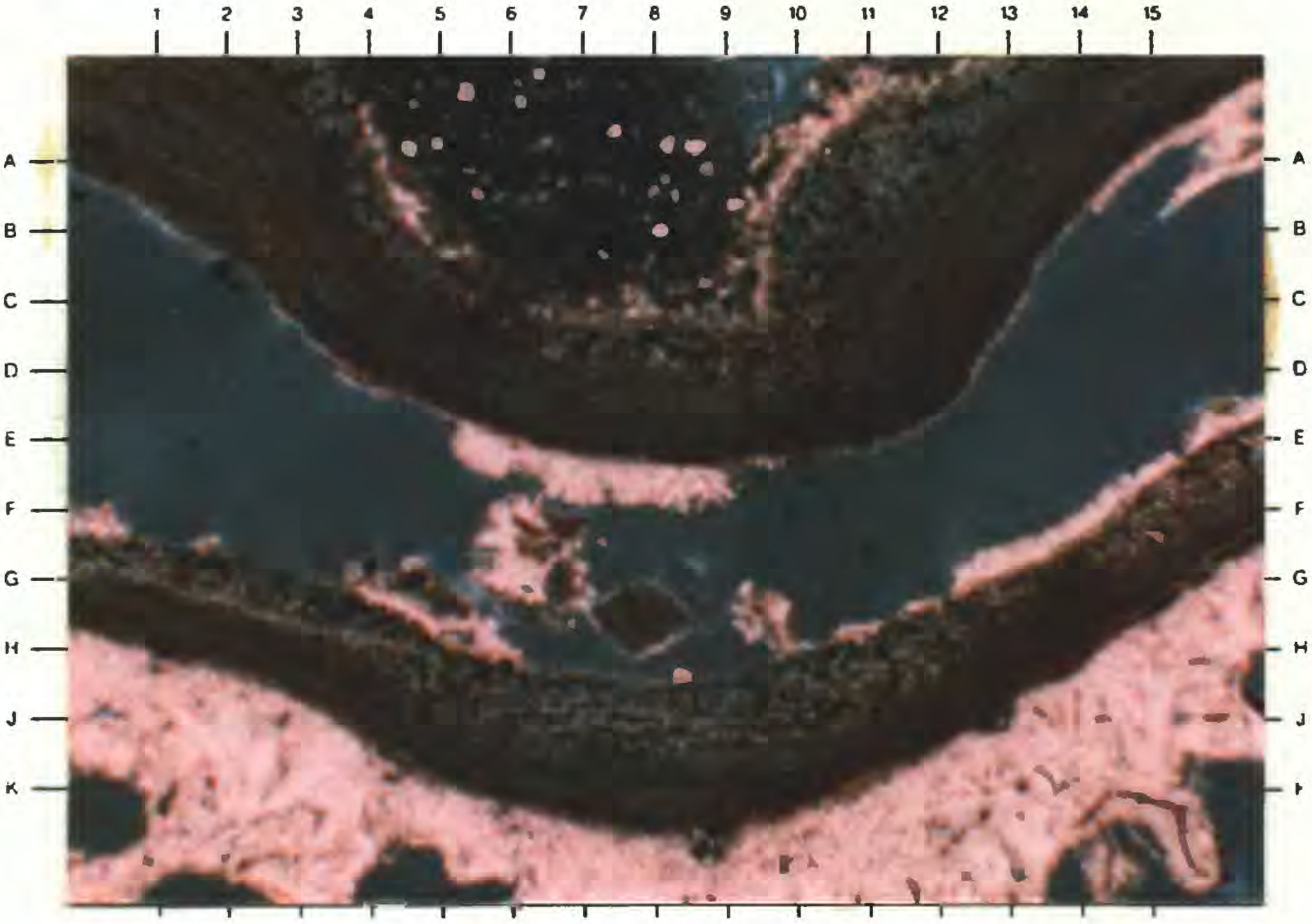
PLATE 7A

Coral-algal boundstone with calcareous red algae encrusting coral. Carbonate detritus is trapped within the red algae (A-7). Needles of aragonite partially rim central void with well-developed crystal splays (E-7) of acicular needles. Partially crossed nicols, distance across photograph: 2.3 mm.

Hole 2 Depth 0.53 m

PLATE 7B

Bioclastic wackestone. A large bivalve shell fragment in the lower part of the photograph represents the dominant clast type. Smaller clasts include a gastropod (E-6) and other unidentifiable shell fragments. Pores are lined with a thin isopachous rim of aragonitic cement (H-12). The outer part of the shell fragment shows a dark micritic envelope. Partially crossed nicols, distance across photograph: 2.3 mm.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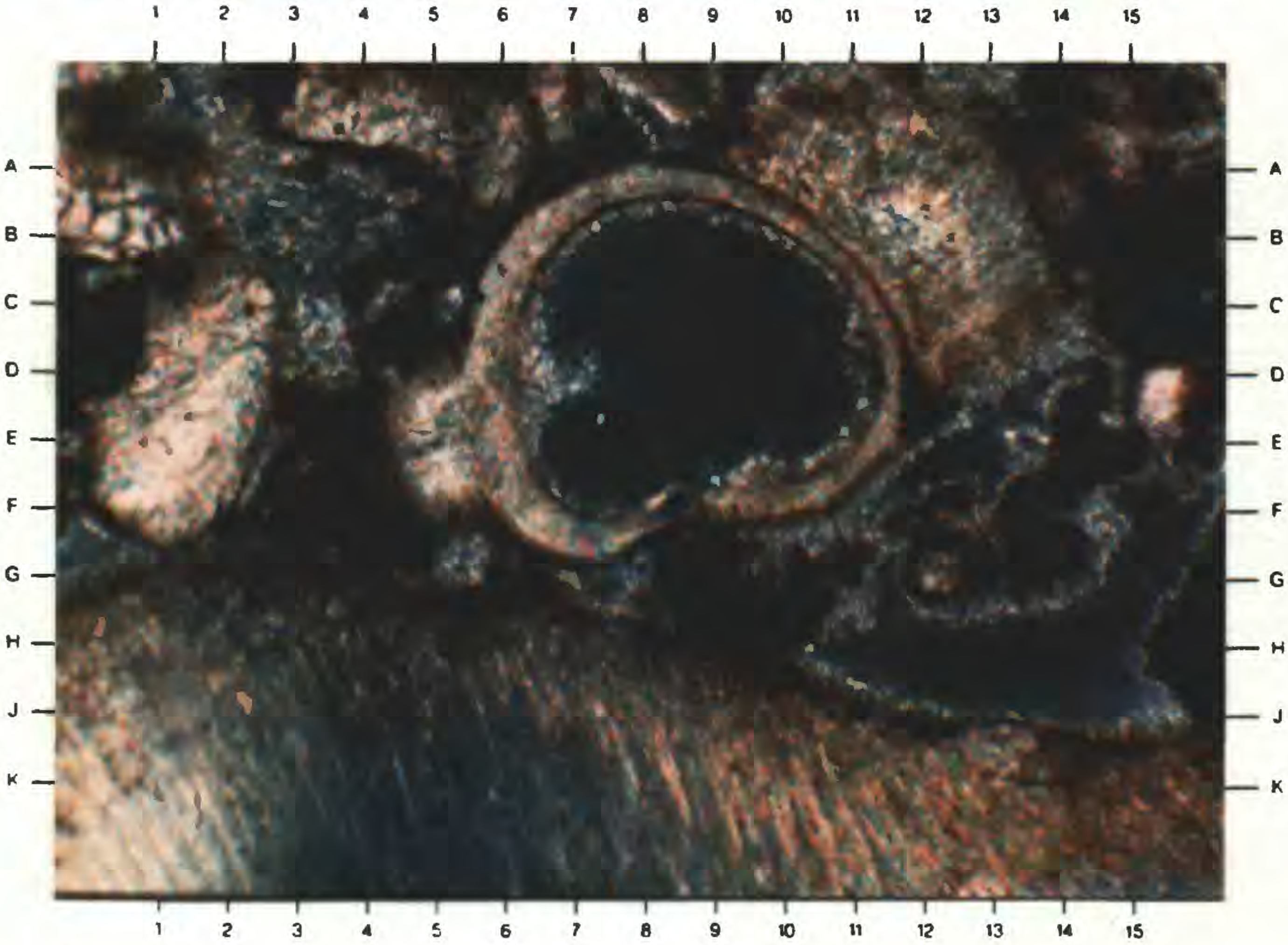
A B C D E F G H J K

A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A B C D E F G H J K

B

Hole 2 Depth 10.73 m

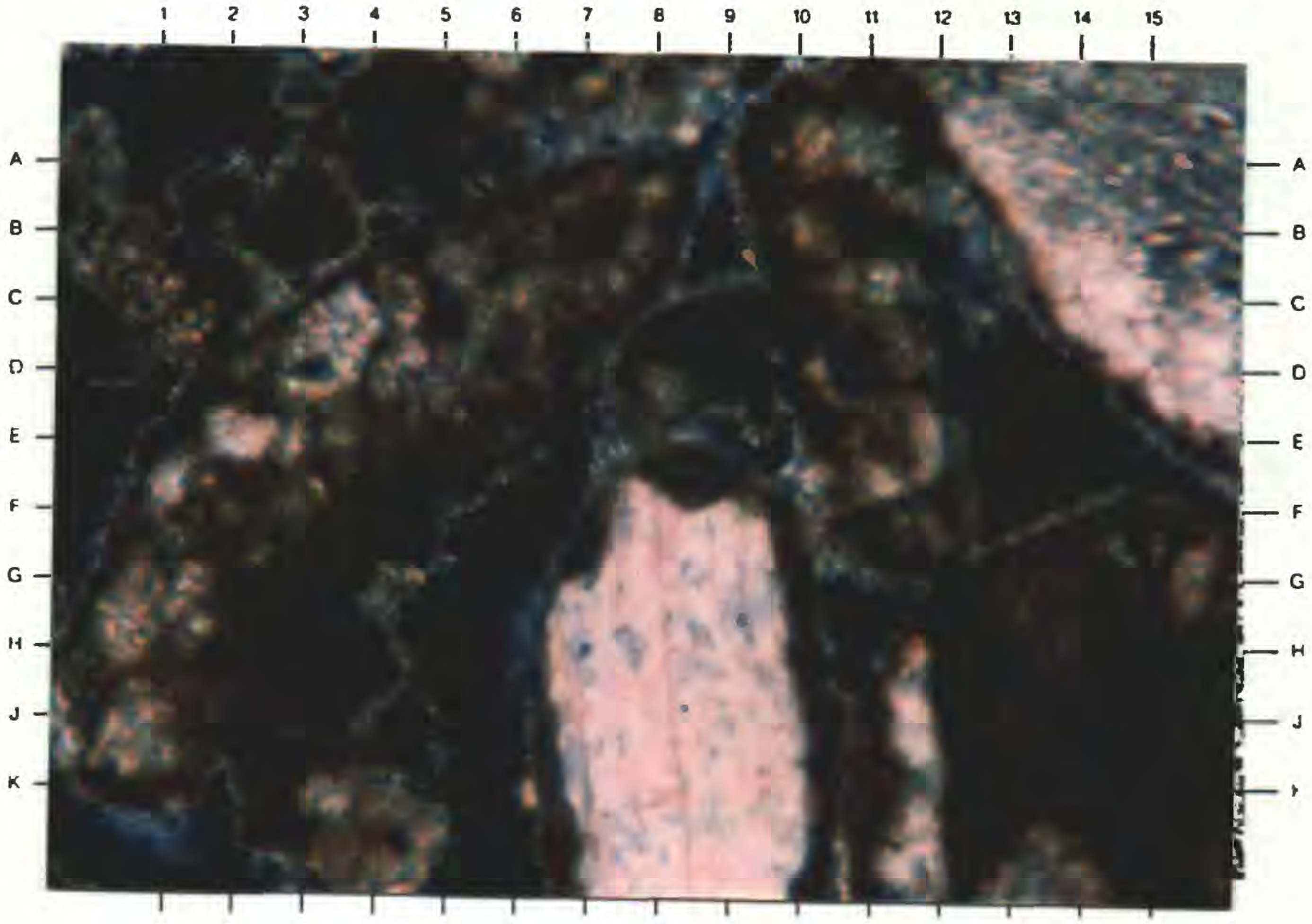
PLATE 8A

Clasts of mollusks (J-9) and *Halimeda* (E-5) underwent neomorphism to sparry calcite. The fragments are rimmed with well-developed micritic envelopes (F-9). The intergranular pores are lined with thin marine phreatic isopachous rims of aragonite. Partially crossed nicols, distance across photograph: 0.56 mm.

Hole 2 Depth 10.88 m

PLATE 8B

A single echinoderm plate bounded by an altered micritic envelope is surrounded by void-filling calcite cement. Partially crossed nicols, distance across photograph: 2.3 mm.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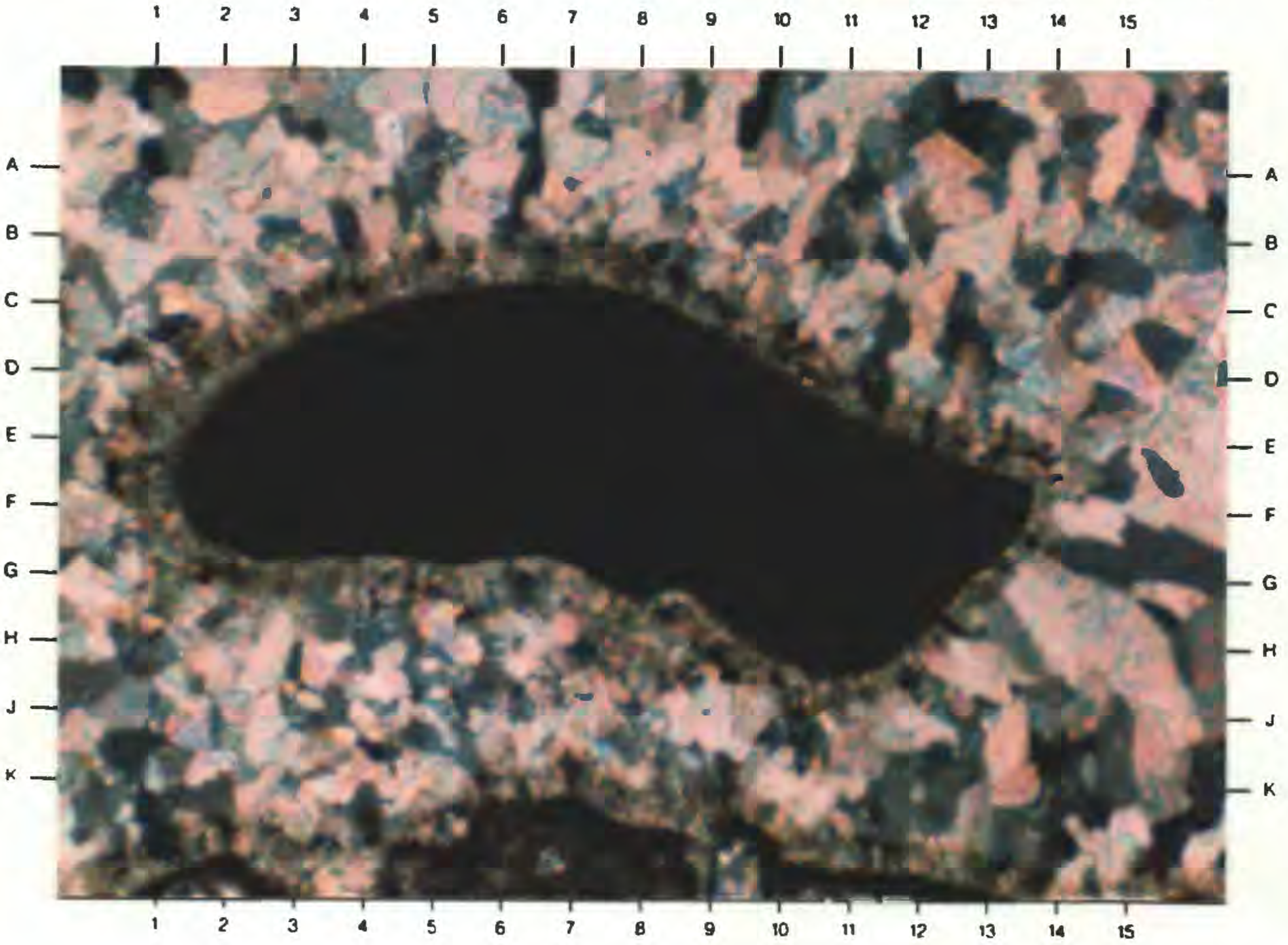
A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A B C D E F G H J K

B

Hole 2 Depth 19.26 m

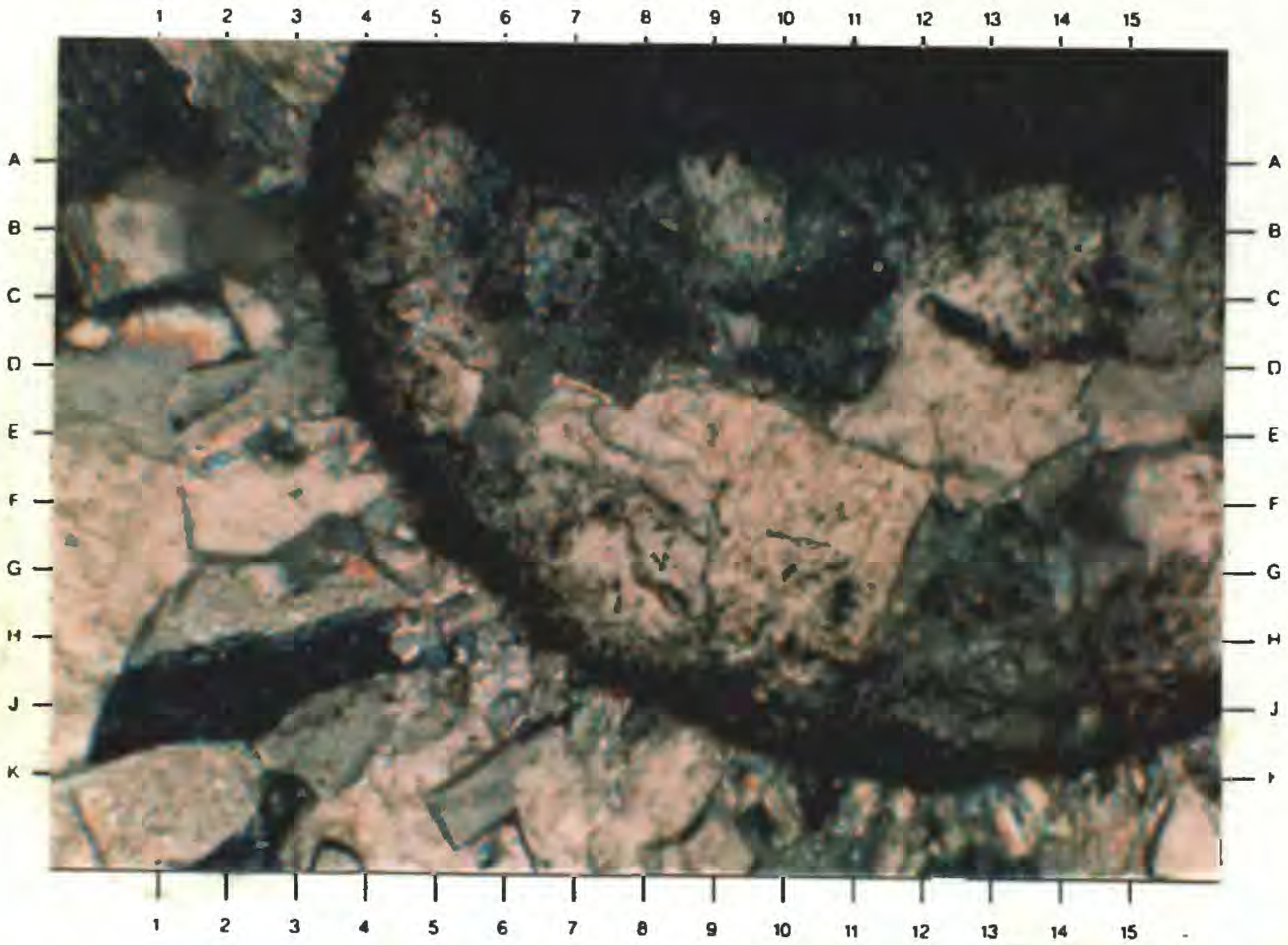
PLATE 9A

Both neomorphic spar and void-filling cement occur. A neomorphosed clast is marked by a dark micritic envelope. The cement crystals show an increase in grain size away from the clast, which is typical of void-fill. Partially crossed nicols, distance across photograph: 2.3 mm.

Hole 2 Depth 35.40 m

PLATE 9B

Massive coral recrystallized from aragonite to calcite. The meandering structures represent the internal skeletal trabecular processes. Growth-framework porosity is maintained. Partially crossed nicols, distance across photograph: 1.5 mm.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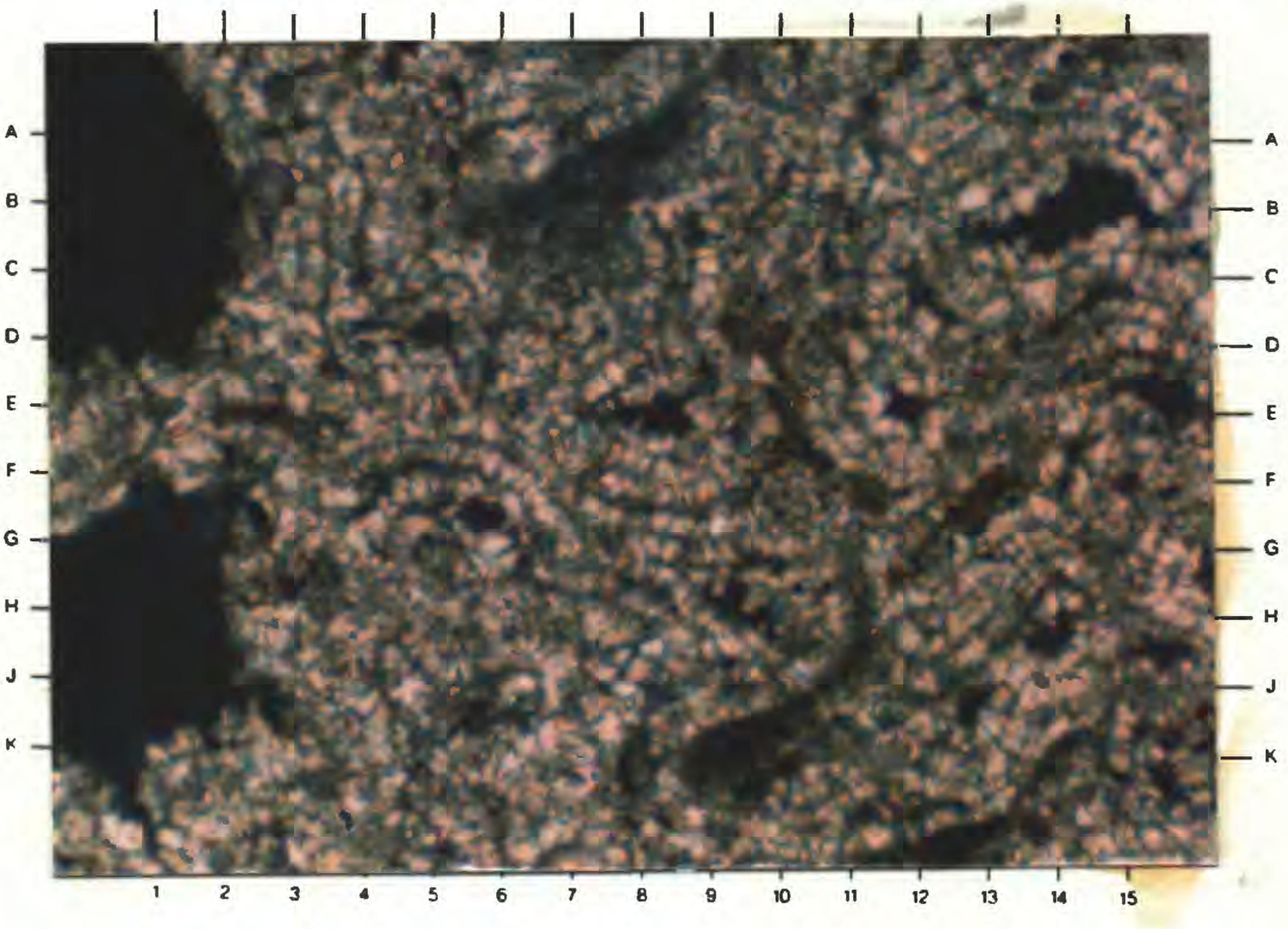
A B C D E F G H J K

A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A B C D E F G H J K

B

Hole 2 Depth 48.12 m

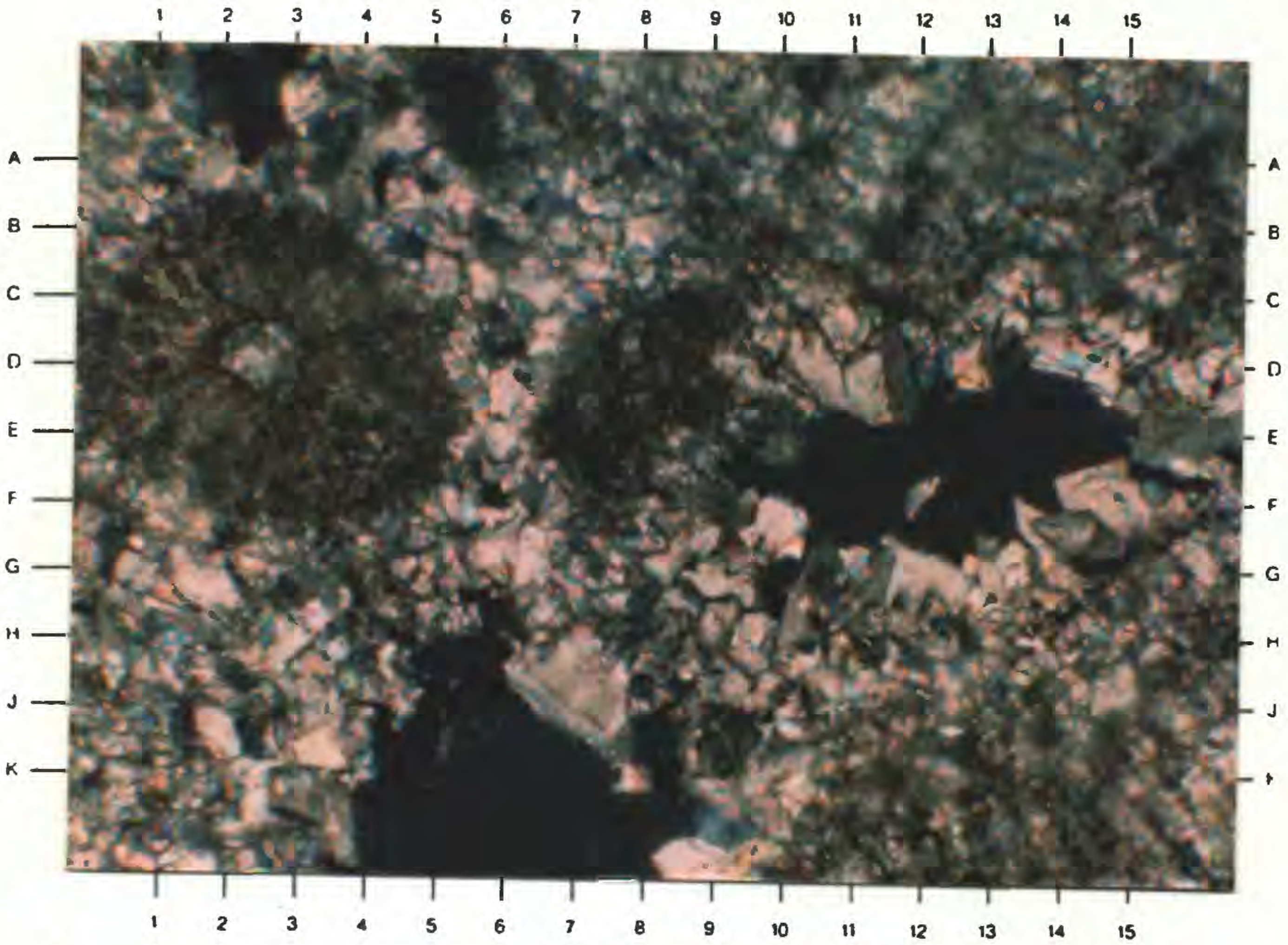
PLATE 10A

Crystalline dolomite contains ghosts of echinoderm plates (D-3), unidentifiable clasts (J-13), and pores (E-12). Former calcite void-filling cement was dolomitized (G-9). Partially crossed nicols, distance across photograph: 0.56 mm.

Hole 2 Depth 48.12 m

PLATE 10B

Calcite void-filling cement altered to dolomite. Dolomite rhombs are superimposed upon the calcite (D-8). Partially crossed nicols, distance across photograph: 0.56 mm.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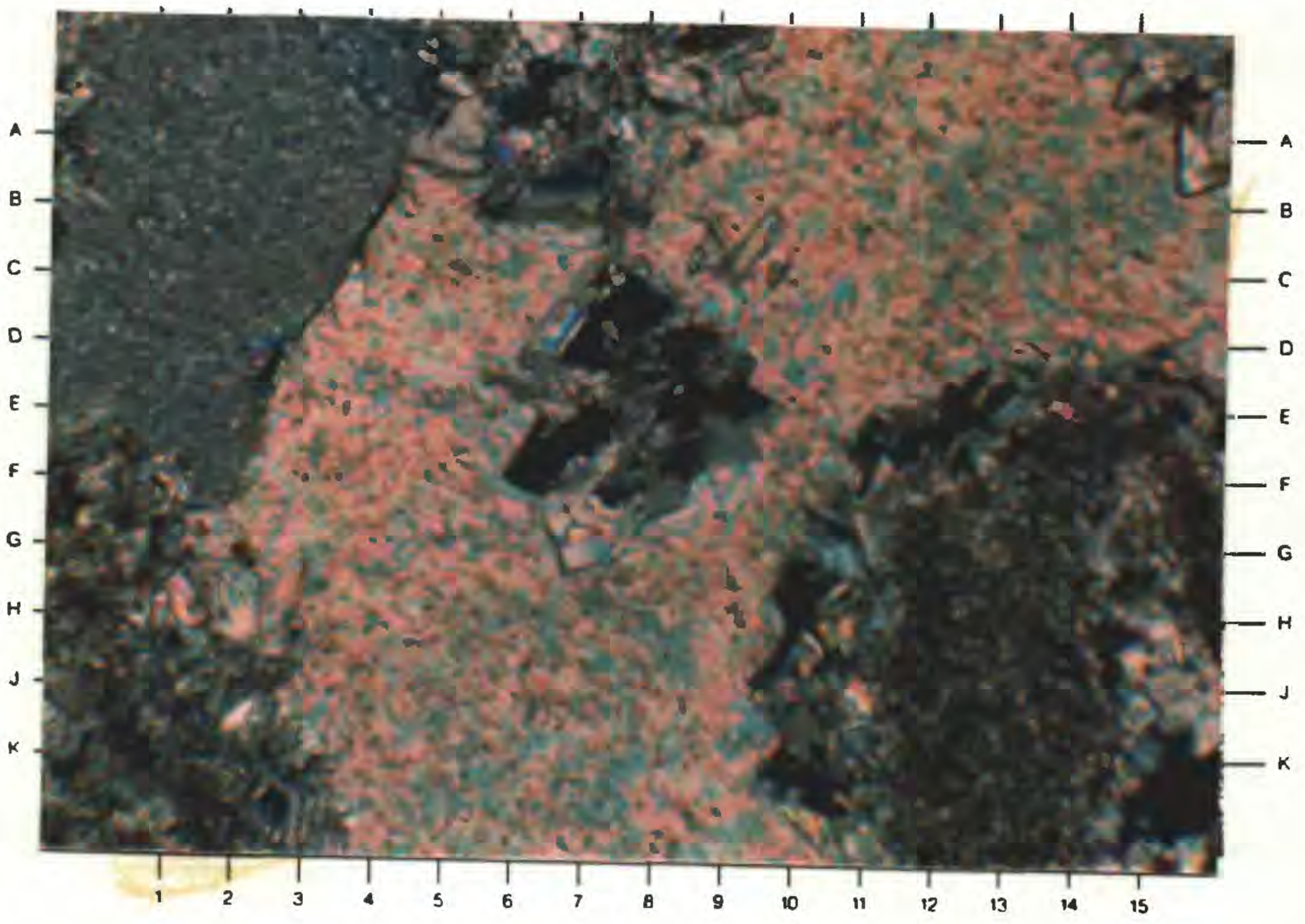
A


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
A B C D E F G H J K

B

Hole 2 Depth 48.12 m

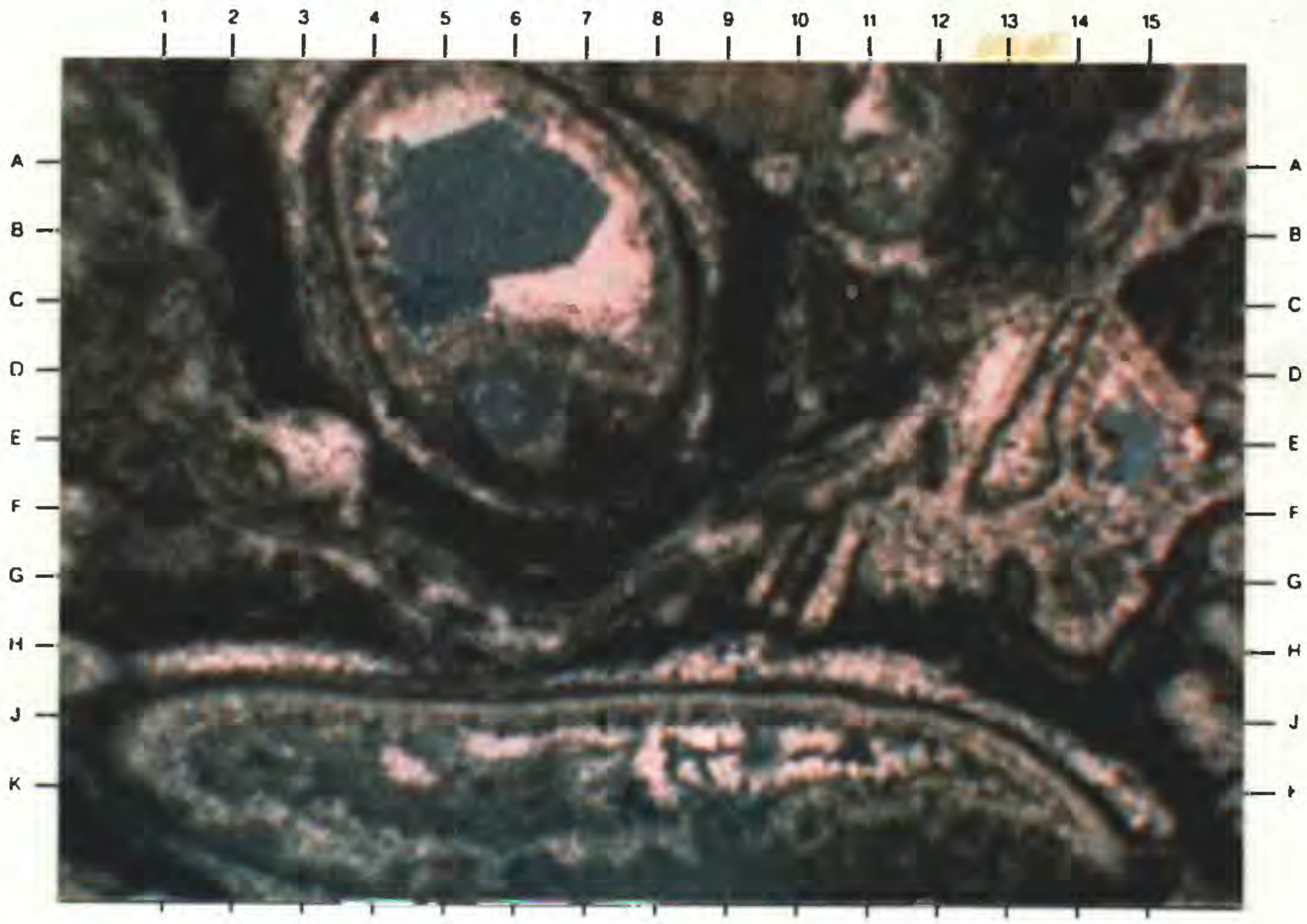
PLATE 11A

Infilled and cemented worm tubes at varying stages of collapse. The best preserved worm tube (D-4) shows geopetal fabric marked by a large void-filling crystal overlying recrystallized detrital micrite. In contrast, the elongated, collapsed worm tube at the base of the photograph has little void-filling cement. Worm tubes are bounded by micritic envelopes (F-8), (J-8). Partially crossed nicols, distance across photograph: 2.3 mm.

Hole 2 Depth 60.08 m

PLATE 11B

Worm tubes in a fine-grained micritic matrix. The worm tubes were partly or completely micritized and infilled by detrital micrite producing geopetal fabric. Some of the worm tubes collapsed (E-10). The entire unit was dolomitized. Partially crossed nicols, distance across photograph: 2.3 mm.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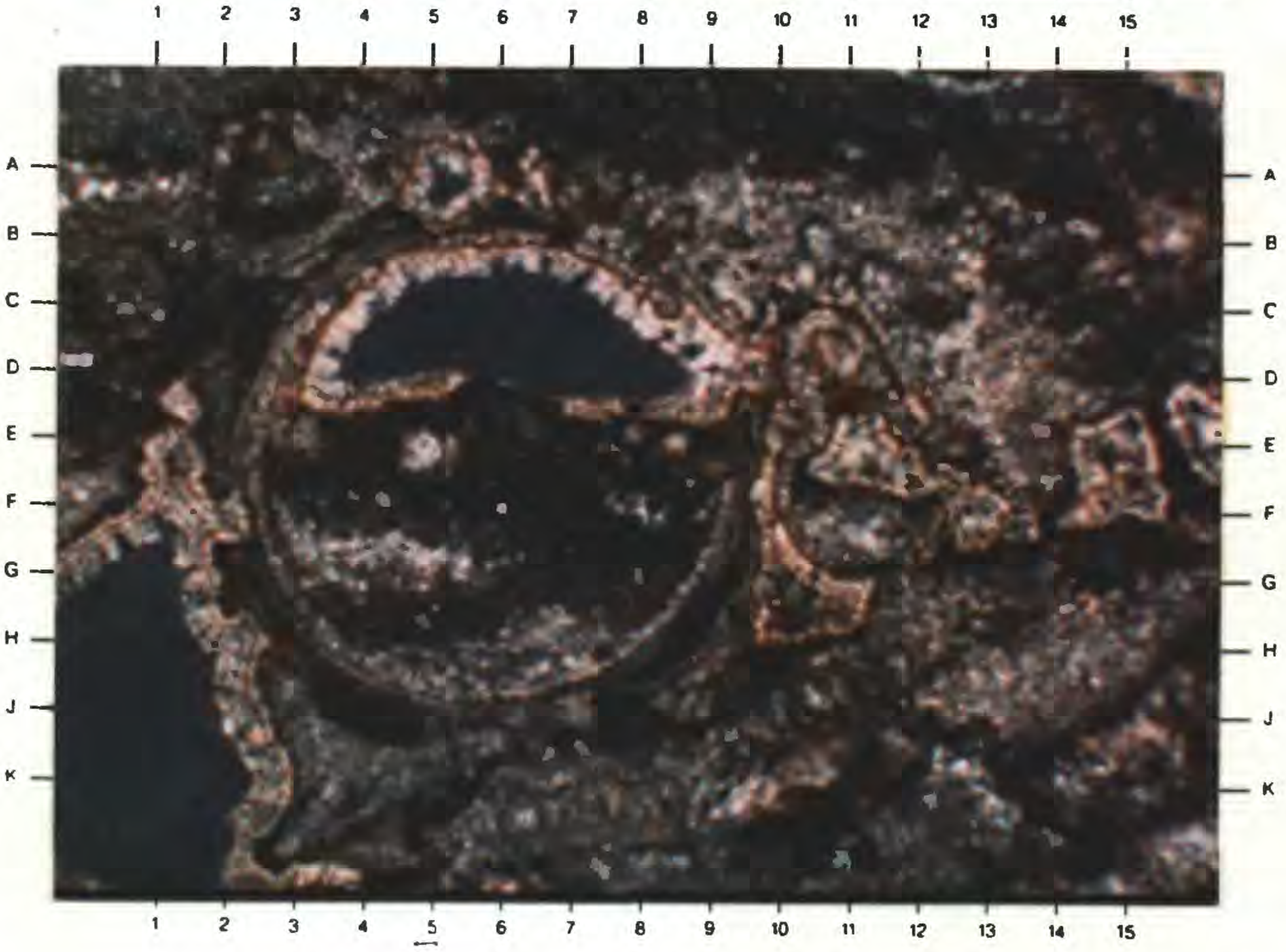
A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A B C D E F G H J K

B

Hole 2 Depth 63.96 m

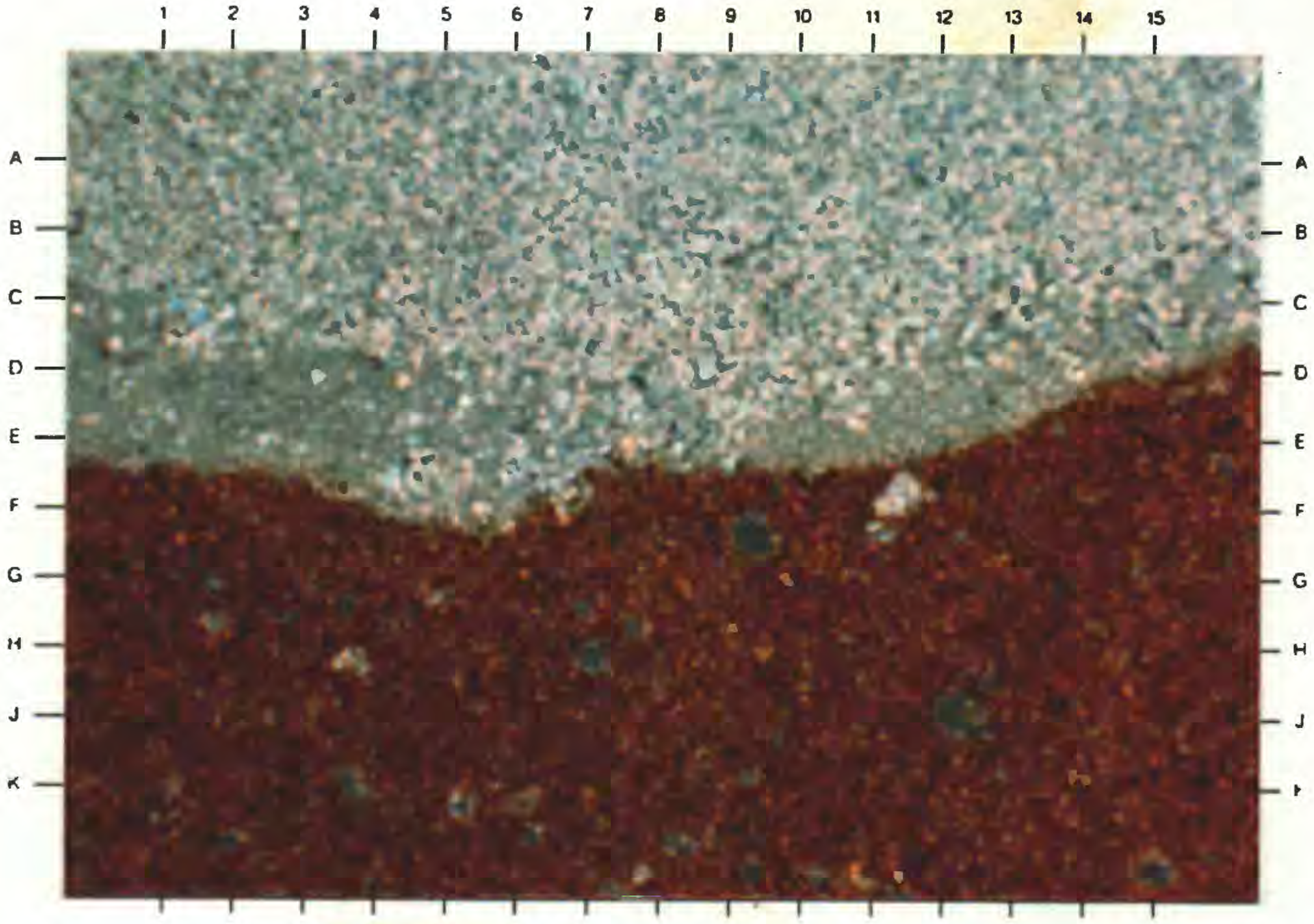
PLATE 12A

Iron-stained and unstained crystalline dolomite are in sharp contact. Note the abundant small molds within the iron-stained area. The molds may represent dissolved foraminiferal tests (see plate 12B). Partially crossed nicols, distance across photograph: 2.3 mm.

Hole 2 Depth 63.96 m

PLATE 12B

Recrystallized foraminiferal test in an iron-stained dolomitic matrix. The foraminiferal test was also dolomitized. Partially crossed nicols, distance across photograph: 0.56 mm.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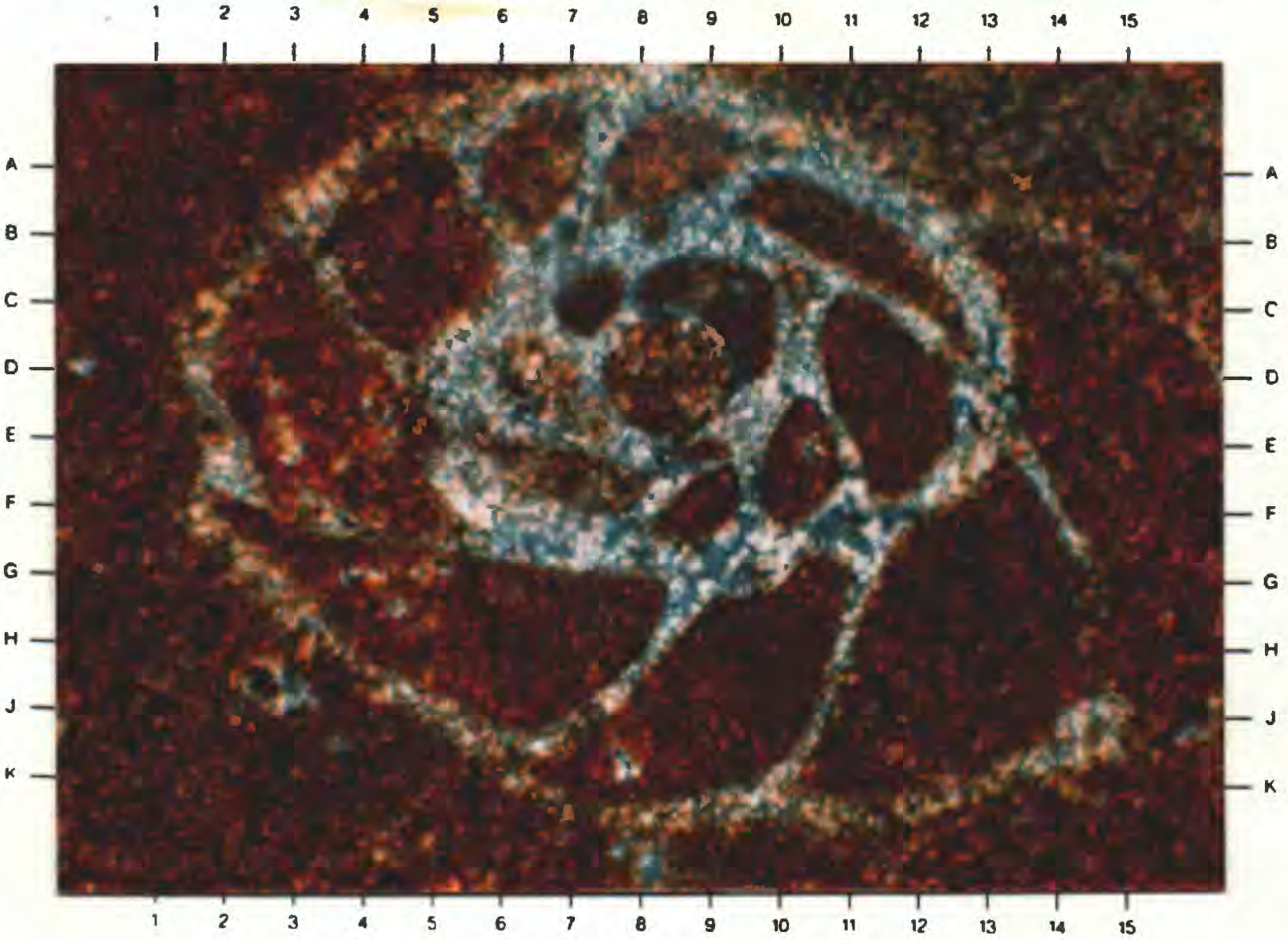
A B C D E F G H J K

A


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
A B C D E F G H J K

B

Hole 2 Depth 63.96 m

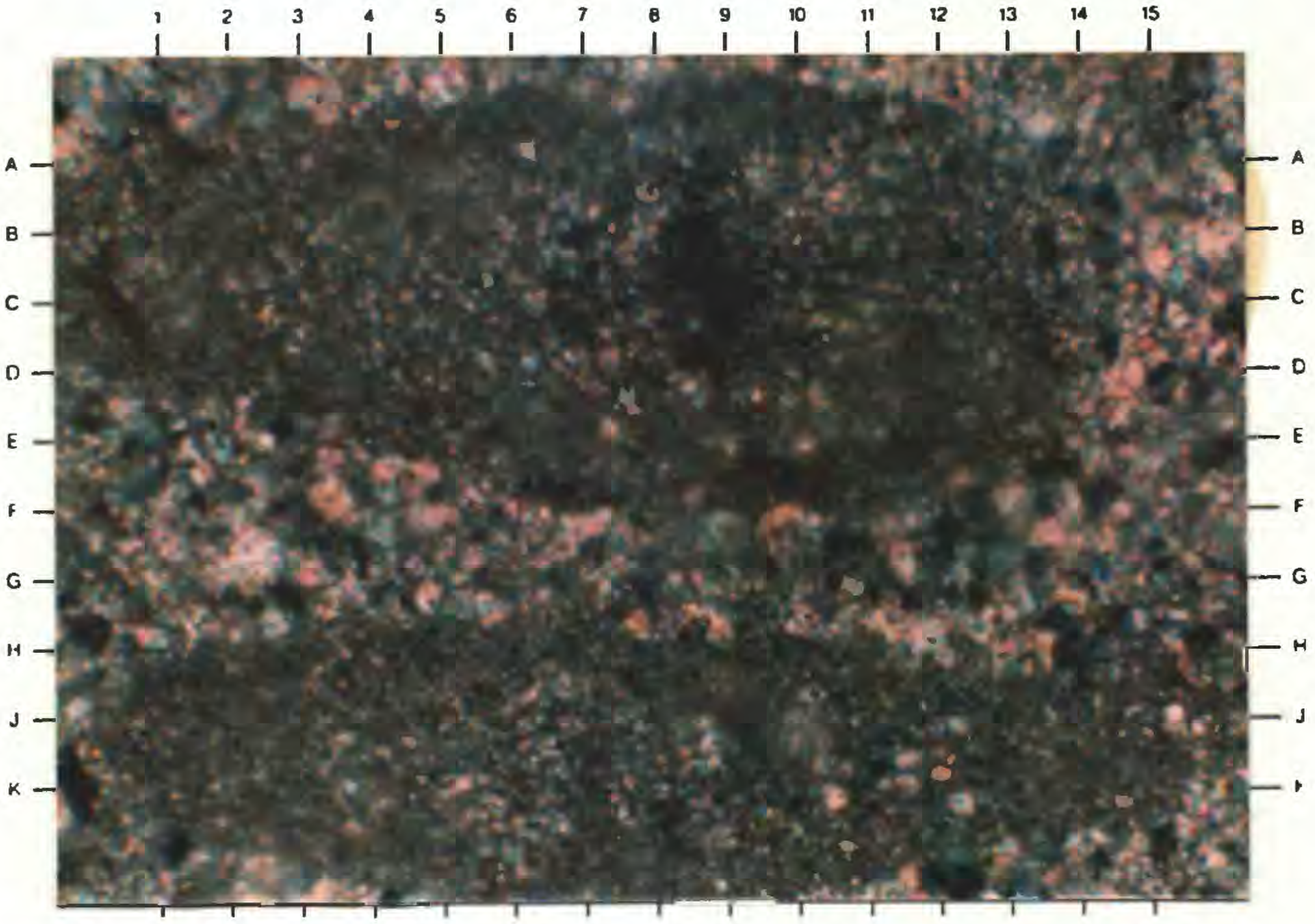
PLATE 13A

Crystalline dolomite showing ghosts of red algal clasts. Partially crossed nicols, distance across photograph: 0.56 mm.

Hole 2 Depth 67.56 m

PLATE 13B

Dolomitized coral wall and septa with detrital infilling of the coral calix. Dark remnant organic matter occurs within the coral wall (B-5). Partially crossed nicols, distance across photograph: 0.23 mm.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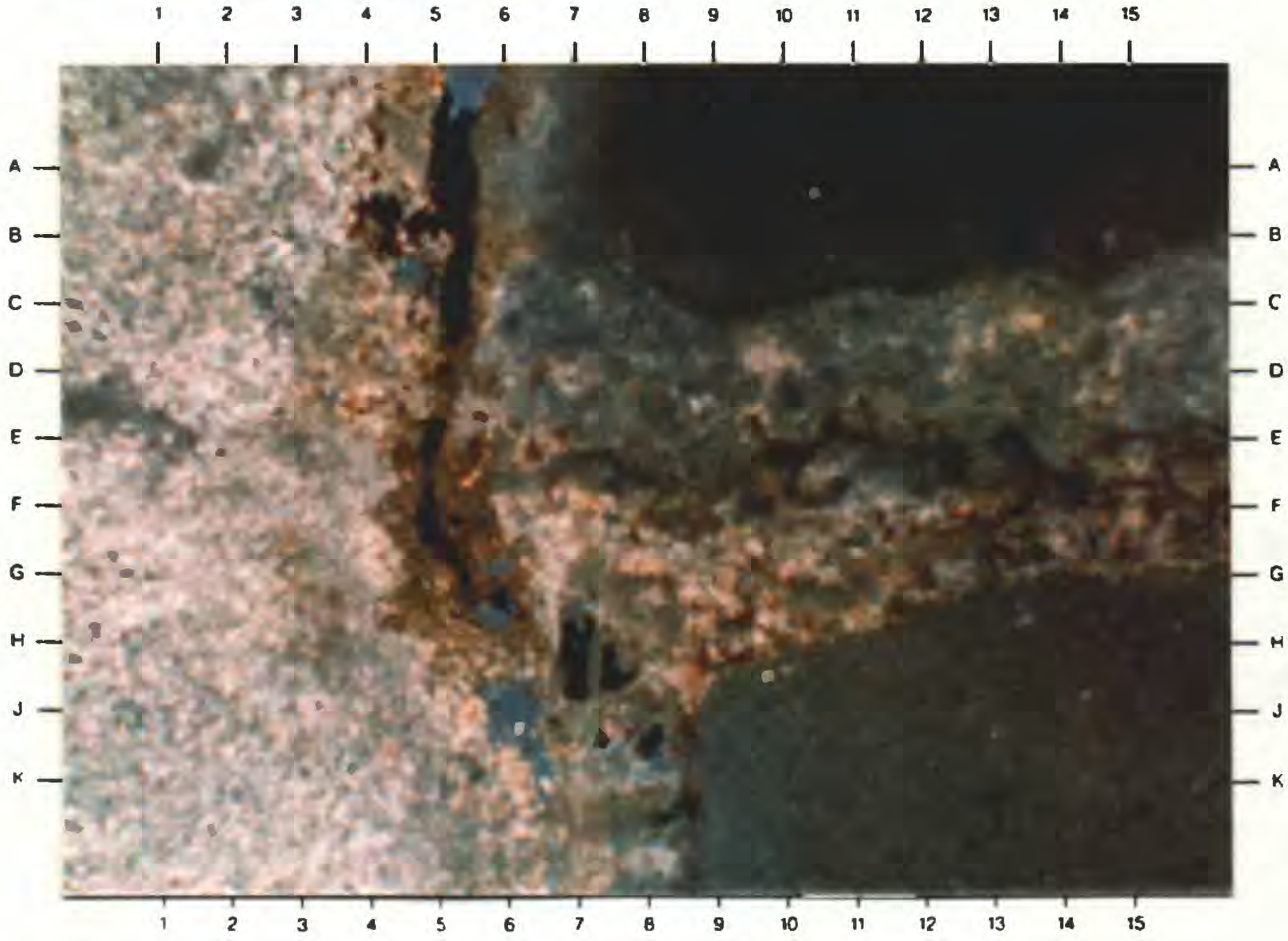
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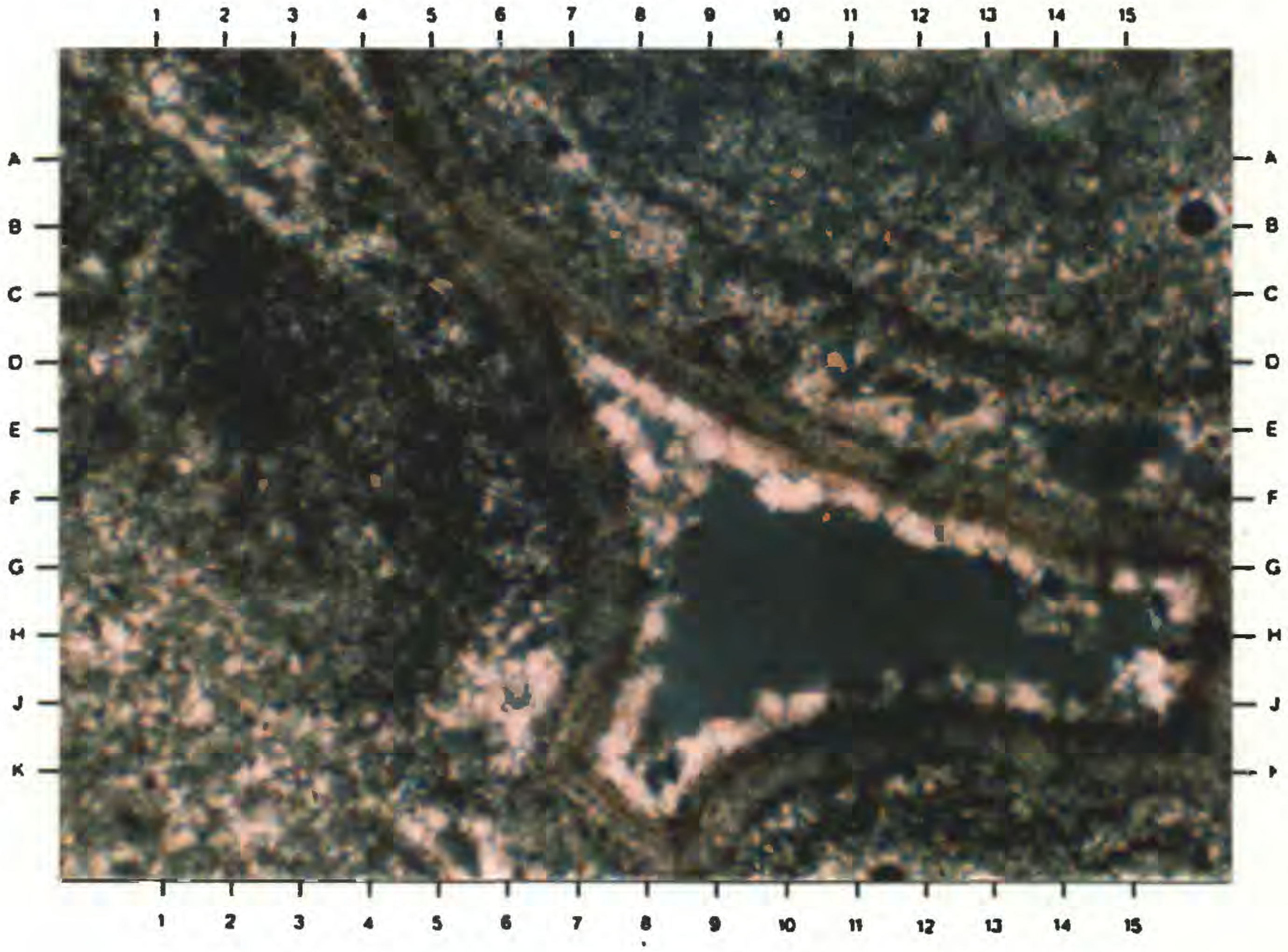


A

Hole 2

Depth 69.10 m

PLATE 14A

The bivalve fragment dominating the photograph of this dolomite reveals a complex diagenetic history: micritization, dissolution of unmicritized part of the shell, precipitation of void-filling isopachous rim cement, partial dissolution, and dolomitization of the calcite. Partially crossed nicols, distance across photograph: 1.5 mm.

Hole 3 Depth 10.8 m

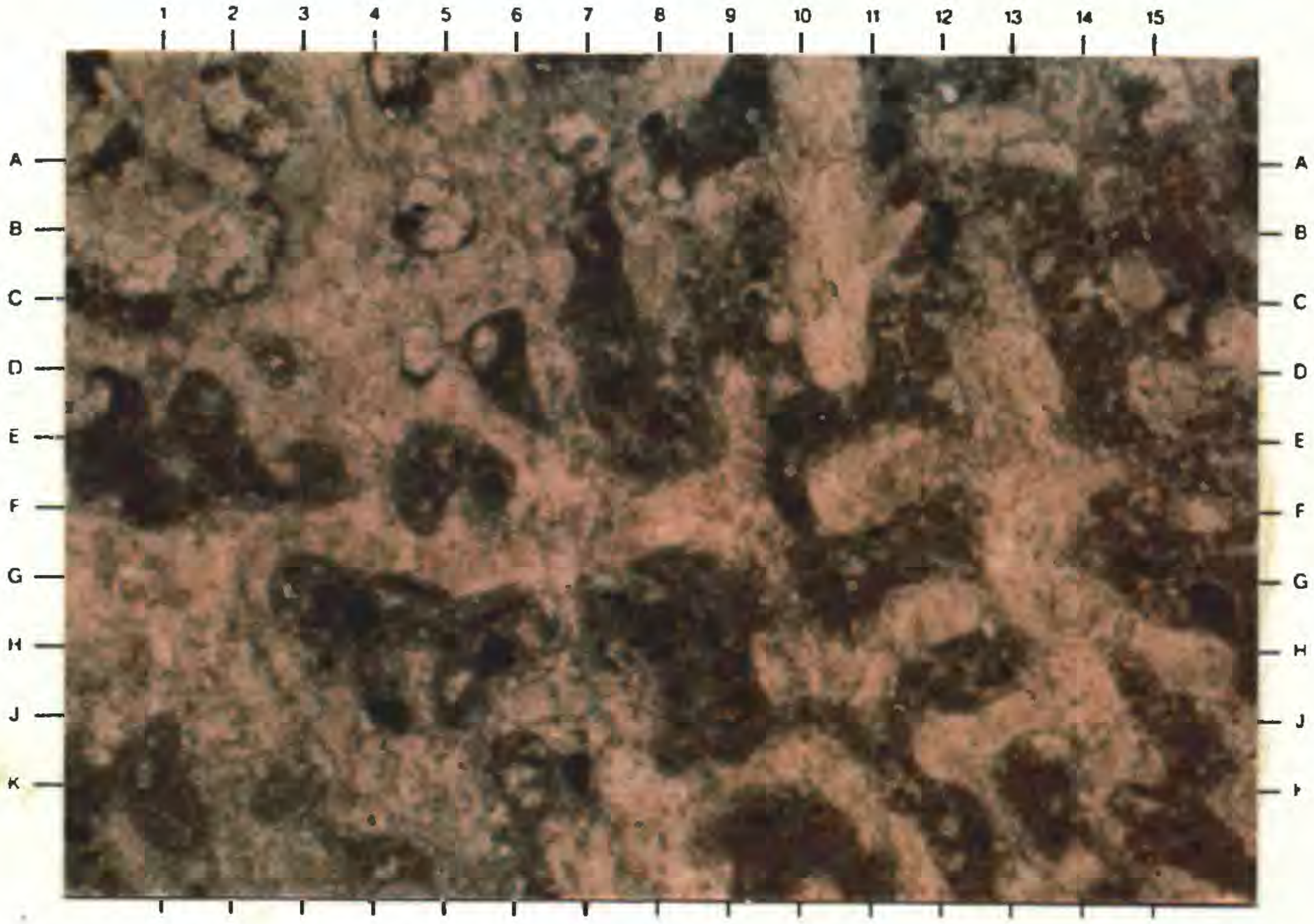
PLATE 15A

Unaltered coral skeleton infilled with detrital micrite and calcite. Within the detrital fill are minerals from weathered basalt (H-6). Sparry calcite, which post-dates the micrite, fills some of the pores (B-2). Plane-polarized light, distance across photograph: 2.3 mm.

Hole 3 Depth 10.8 m

PLATE 15B

Overview of a skeletal grainstone with coral, echinoderm, and mollusk fragments. A large neomorphosed coral fragment (H-3) dominates the field of view. Leached vugs (K-6) and molds (C-9) make up the predominant pore types. Pores are lined with sparry calcite. Detrital micrite with mafic minerals from weathered basalt fill some of the intergranular pore spaces (F-10). Partially crossed nicols, distance across photograph: 2.3 mm.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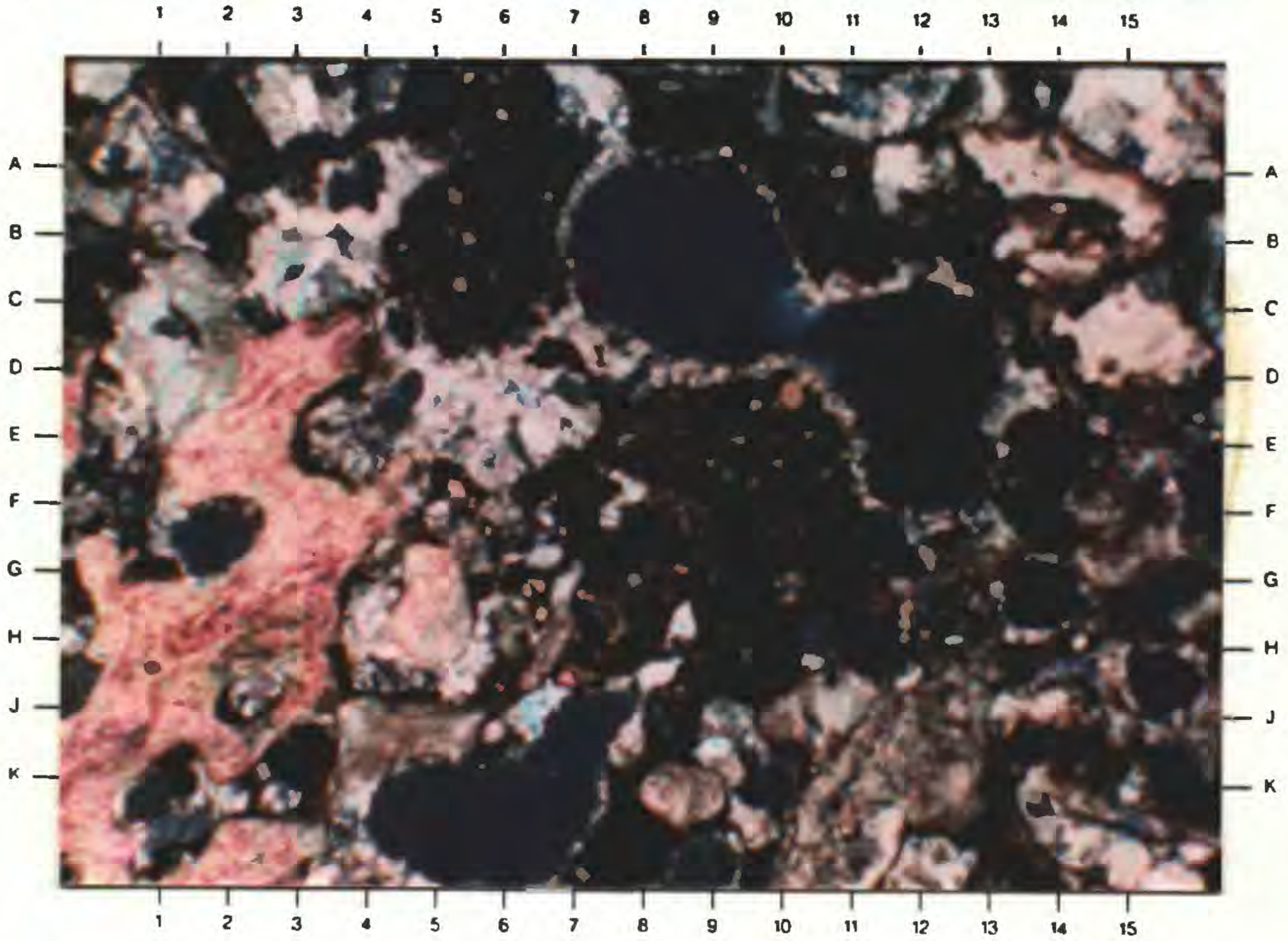
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A B C D E F G H J K

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Hole 3 Depth 11.00 m

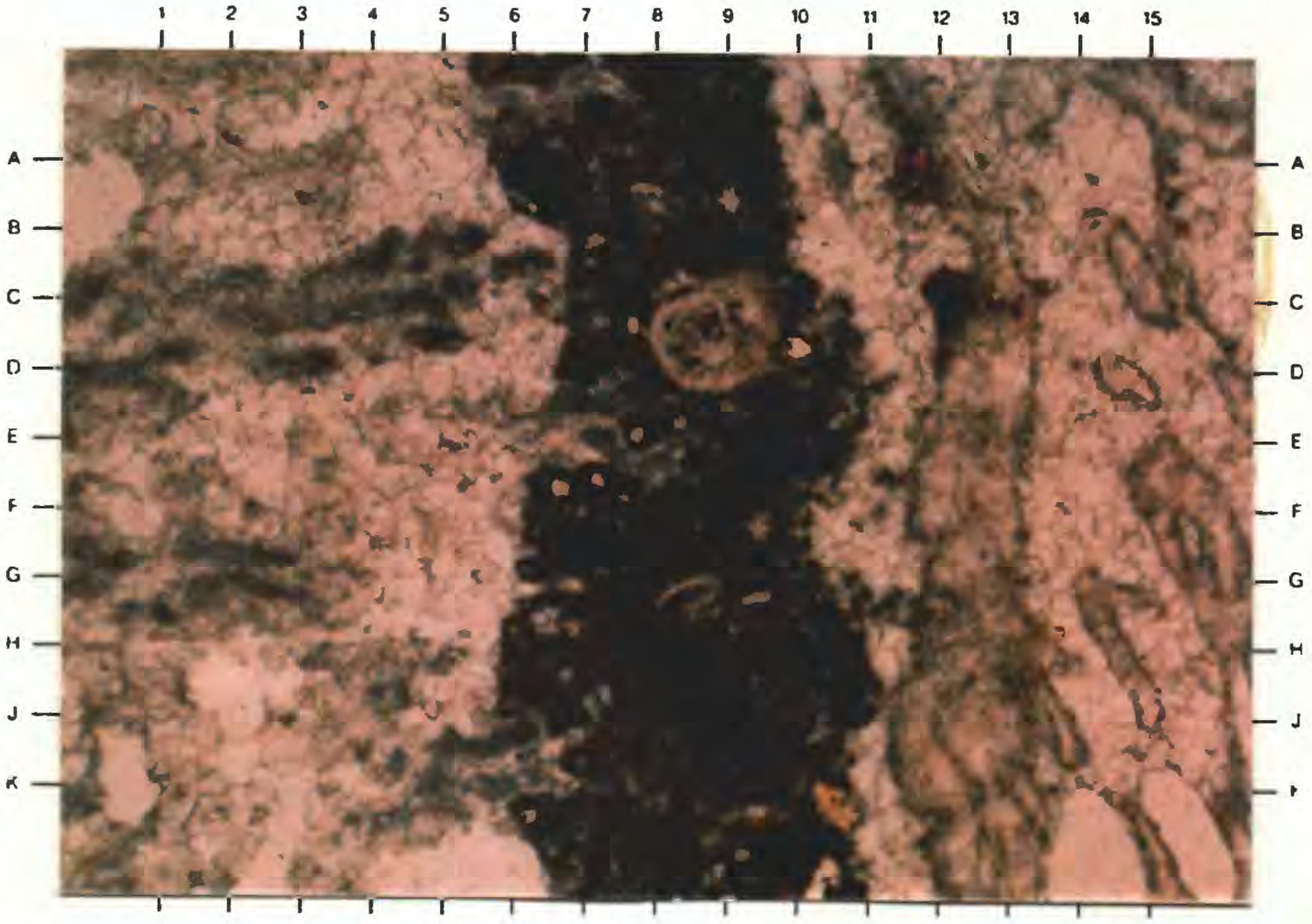
PLATE 16A

Altered coral with detrital micritic infill. The neomorphosed coral skeleton is bounded by a micritic envelope and stands out from the sparry void-filling calcite cement. The detrital micrite contains mafic minerals from weathered basalt, a benthic foraminifera (C-9), and other skeletal fragments. Plane-polarized light, distance across photograph: 2.3 mm.

Hole 3 Depth 14.20 m

PLATE 16B

Overview of a *Halimeda* packstone showing complete to partial neomorphism of *Halimeda* plates. Dissolution of the micritic matrix was followed by void-filling sparry calcite cement. Partially crossed nicols, distance across photograph: 2.3 mm.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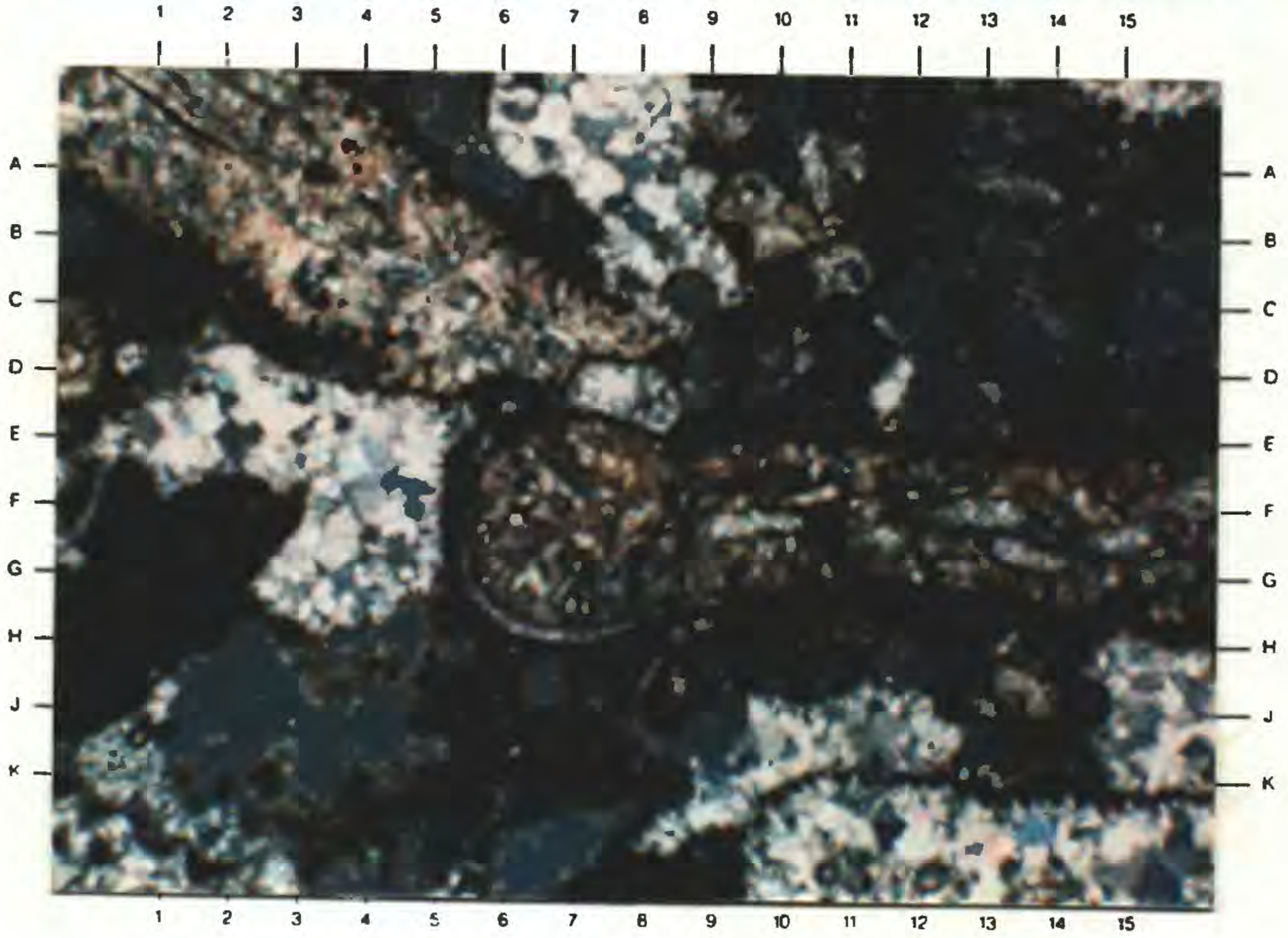
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Hole 4 Depth 1.16 m

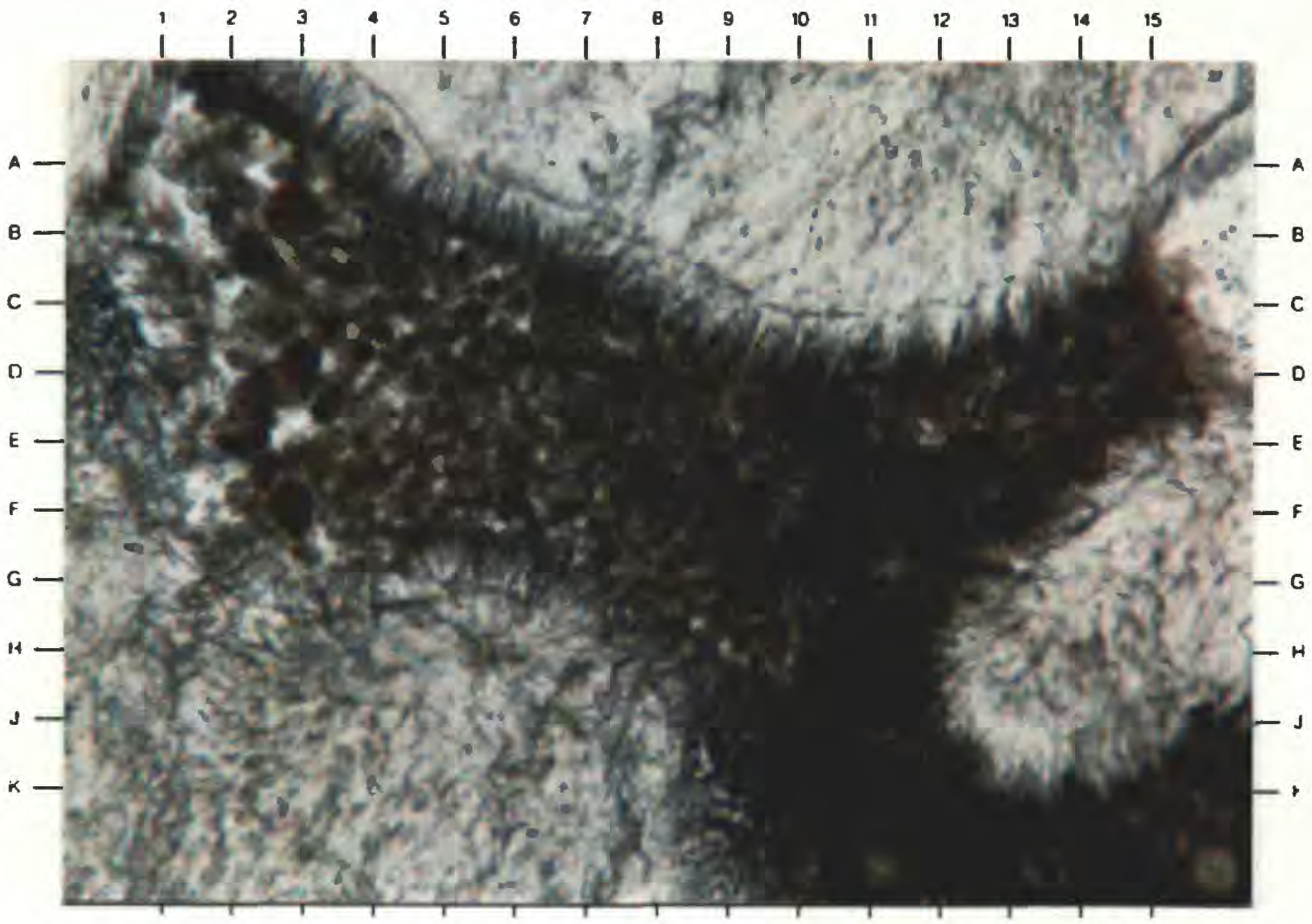
PLATE 17A

Infilled pore of an unaltered coral skeleton. The pore was initially rimmed by an acicular isopachous aragonitic cement and later infilled by pellets of micrite. Plane-polarized light, distance across photograph: 1.5 mm.

Hole 4 Depth 5.87 m

PLATE 17B

Altered coral fragment with pores infilled by micrite and botryoidal aragonitic cement (D-9). Crossed nicols, distance across photograph: 0.56 mm.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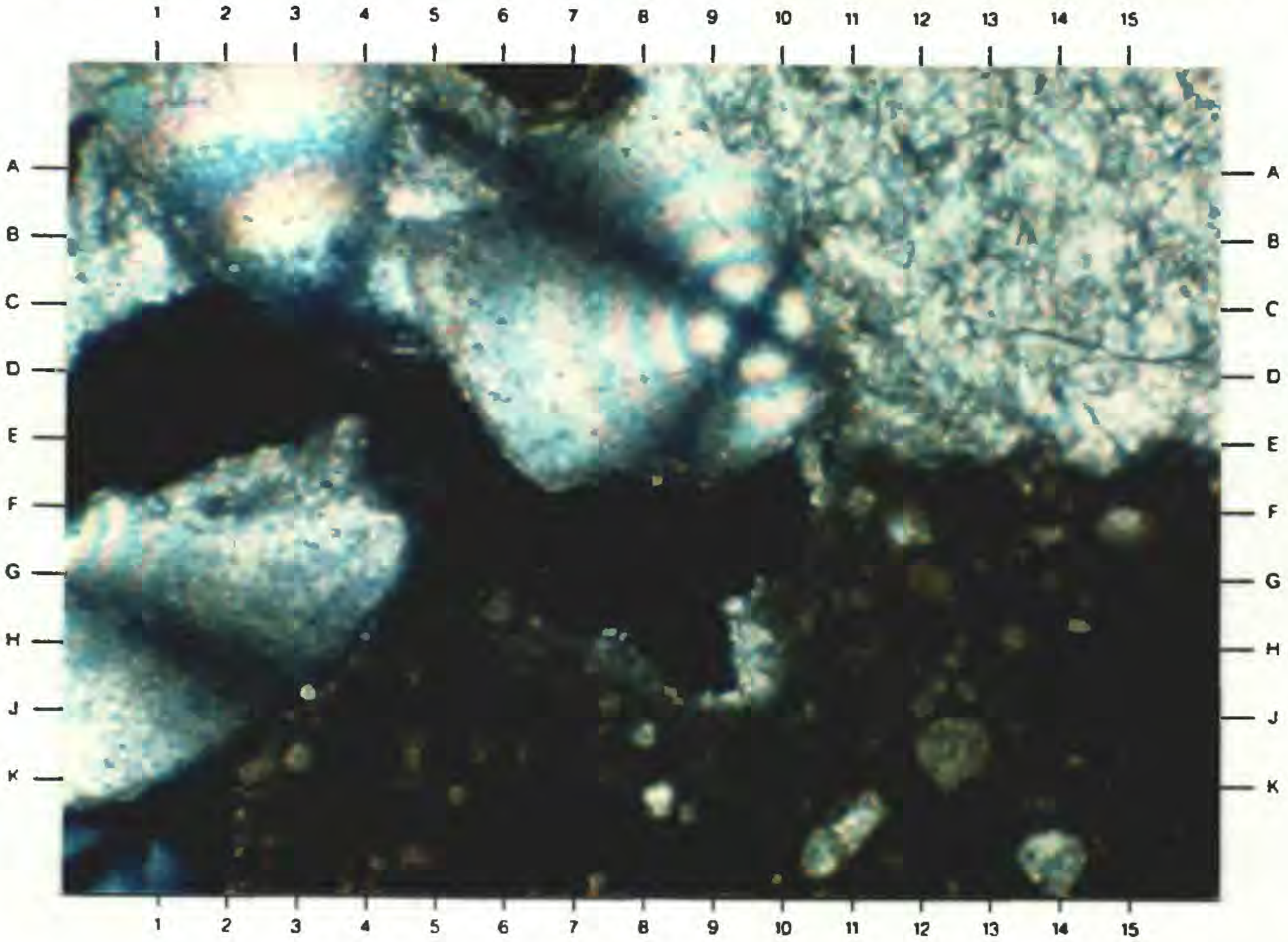
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A B C D E F G H J K

B

Hole 4A Depth 7.10 m

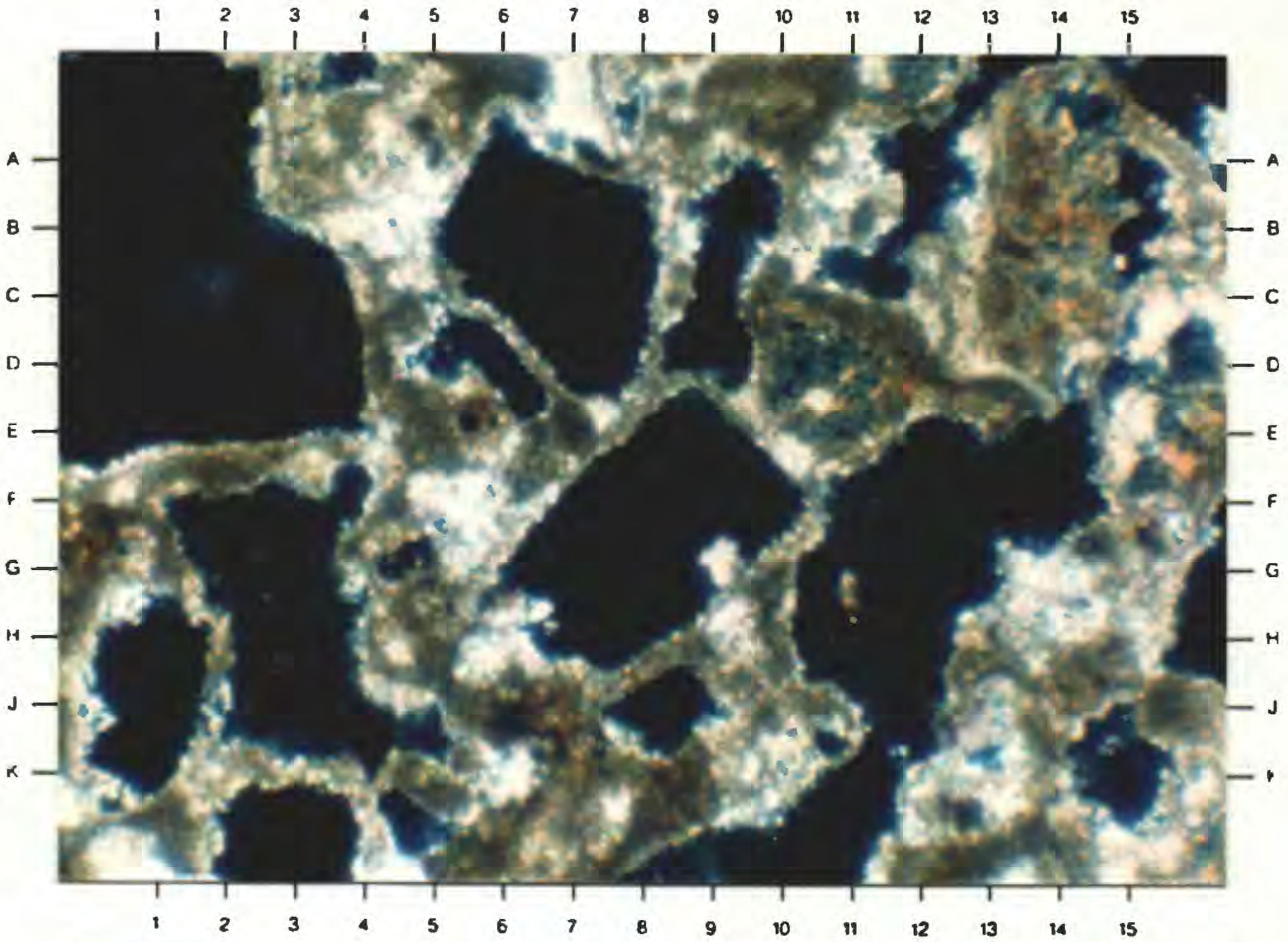
PLATE 18A

Alteration of *Halimeda* packstone with well-developed moldic porosity bounded by free-standing micritic envelopes. Micritization of the skeletal grain was followed by precipitation of void-filling cement. Preferential dissolution of skeletal grains left free-standing micritic envelopes that bound the molds. Partially crossed nicols, distance across photograph: 2.3 mm.

Hole 4A Depth 22.58 m

PLATE 18B

Highly altered skeletal packstone. Early micritization of skeletal grains was followed by neomorphism. The red algae (D-5), surrounding matrix, and skeletal grains were partly dissolved leaving voids that were infilled with sparry calcite cement. Partially crossed nicols, distance across photograph: 2.3 mm.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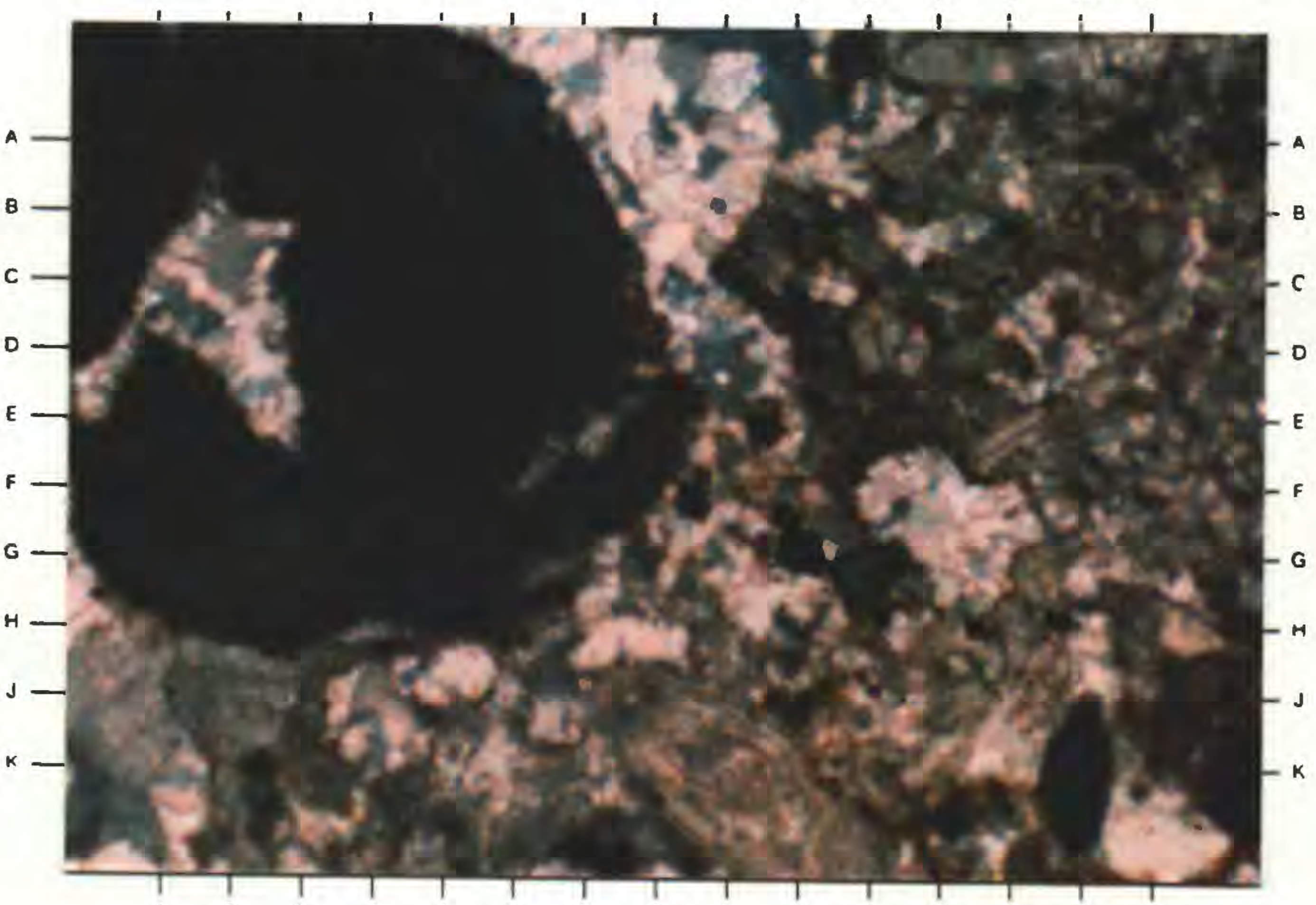
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Hole 5 Depth 16.93 m

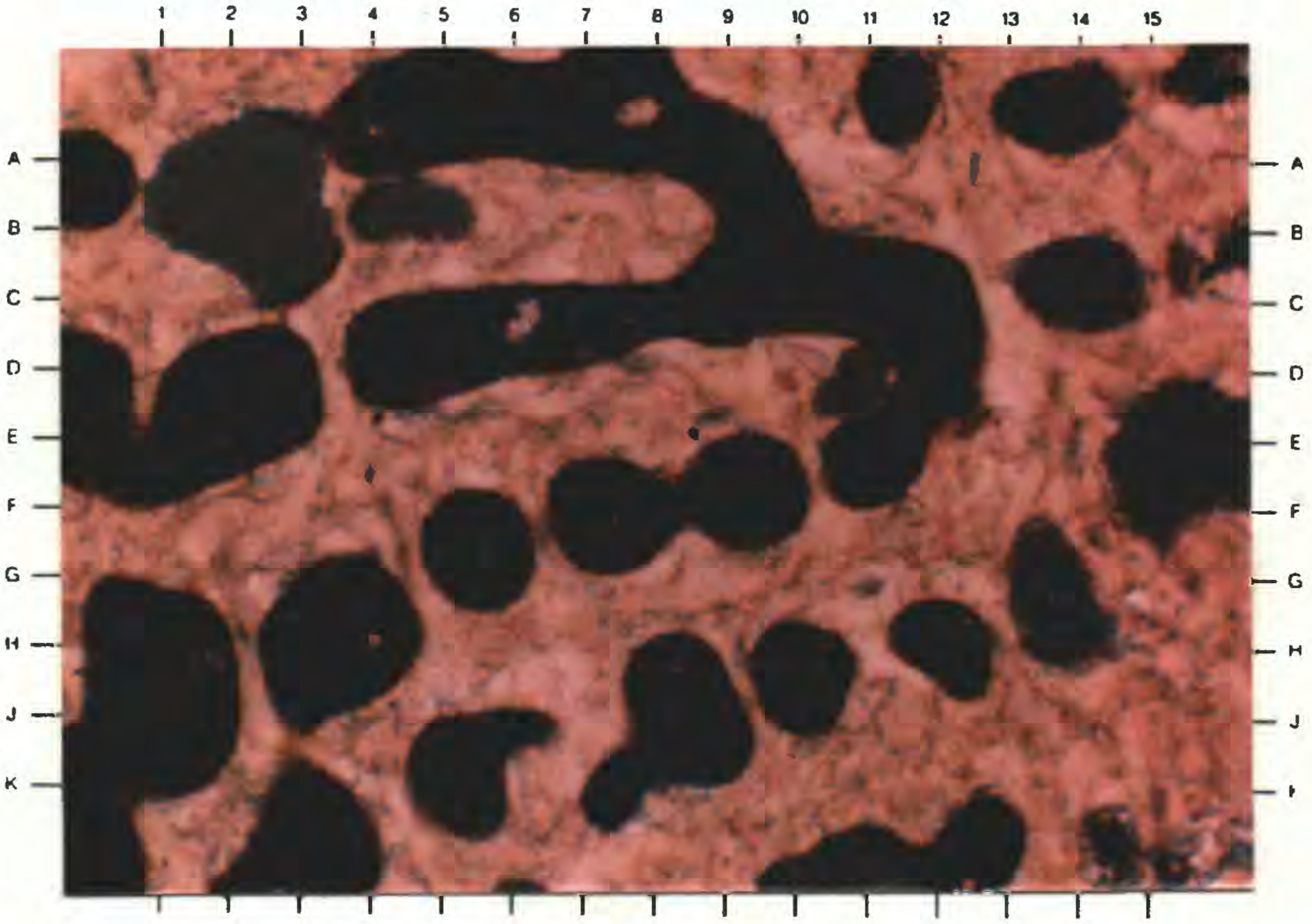
PLATE 19A

An unaltered coral (*Acropora* sp.) contains structural pores and borings that were infilled with detrital micrite. Faint rims of acicular aragonite of marine phreatic origin line the pores (H-12). Partially crossed nicols, distance across photograph: 1.5 mm.

Hole 5 Depth 25.07 m

PLATE 19B

Recrystallized grainstone with foraminifera (A-11, nummulite) and bivalve fragments. A large bivalve fragment (G-11) records a three-step diagenetic history: micritization of the outer layer of the shell, dissolution of the unmicritized part, and void-filling by sparry calcite cement within the mold. Small molds are scattered throughout the calcite matrix (G-3.5). Partially crossed nicols, distance across photograph: 2.3 mm.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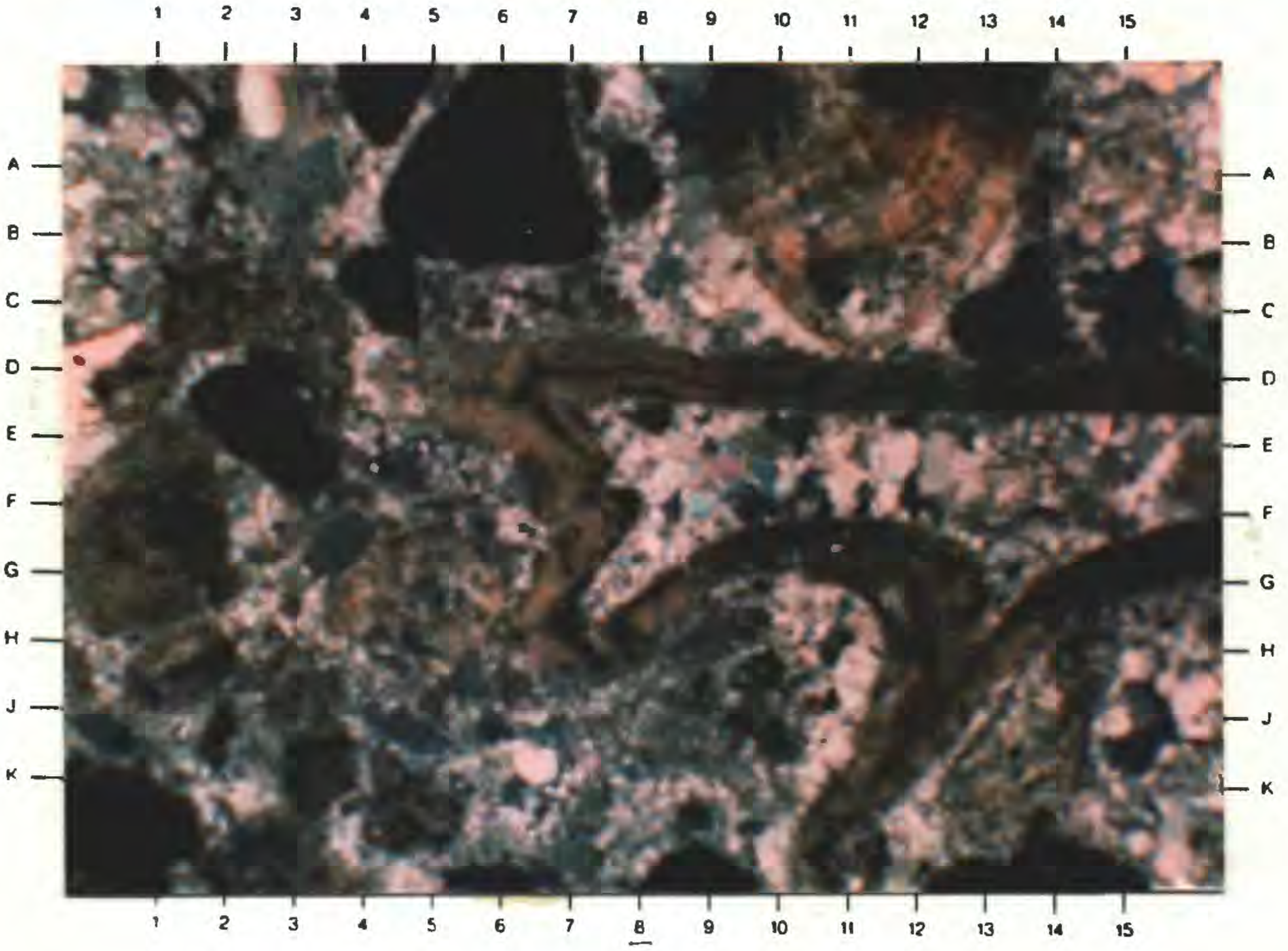
A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A B C D E F G H J K

B

Hole 5 Depth ~46.04 m

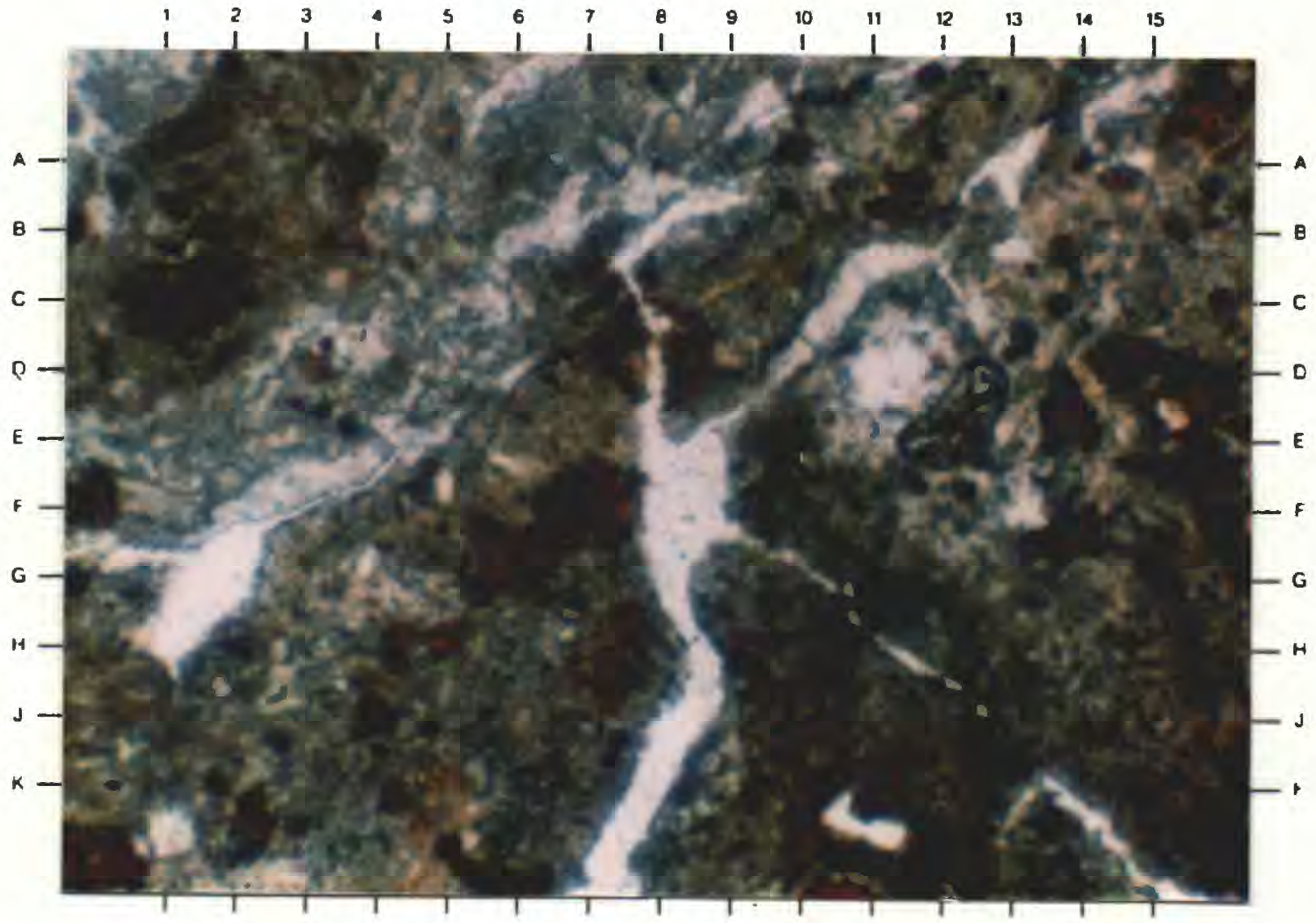
PLATE 20A

Calcite veins cut altered basalt containing reddish-brown secondary goethite. Partially crossed nicols, distance across photograph: 2.3 mm.

Hole 5 Depth 52.02 m

PLATE 20B

Dolomitization of void-filling calcite cement. Dolomite rhombs are scattered throughout the rock (G-7). Partially crossed nicols, distance across photograph: 0.56 mm.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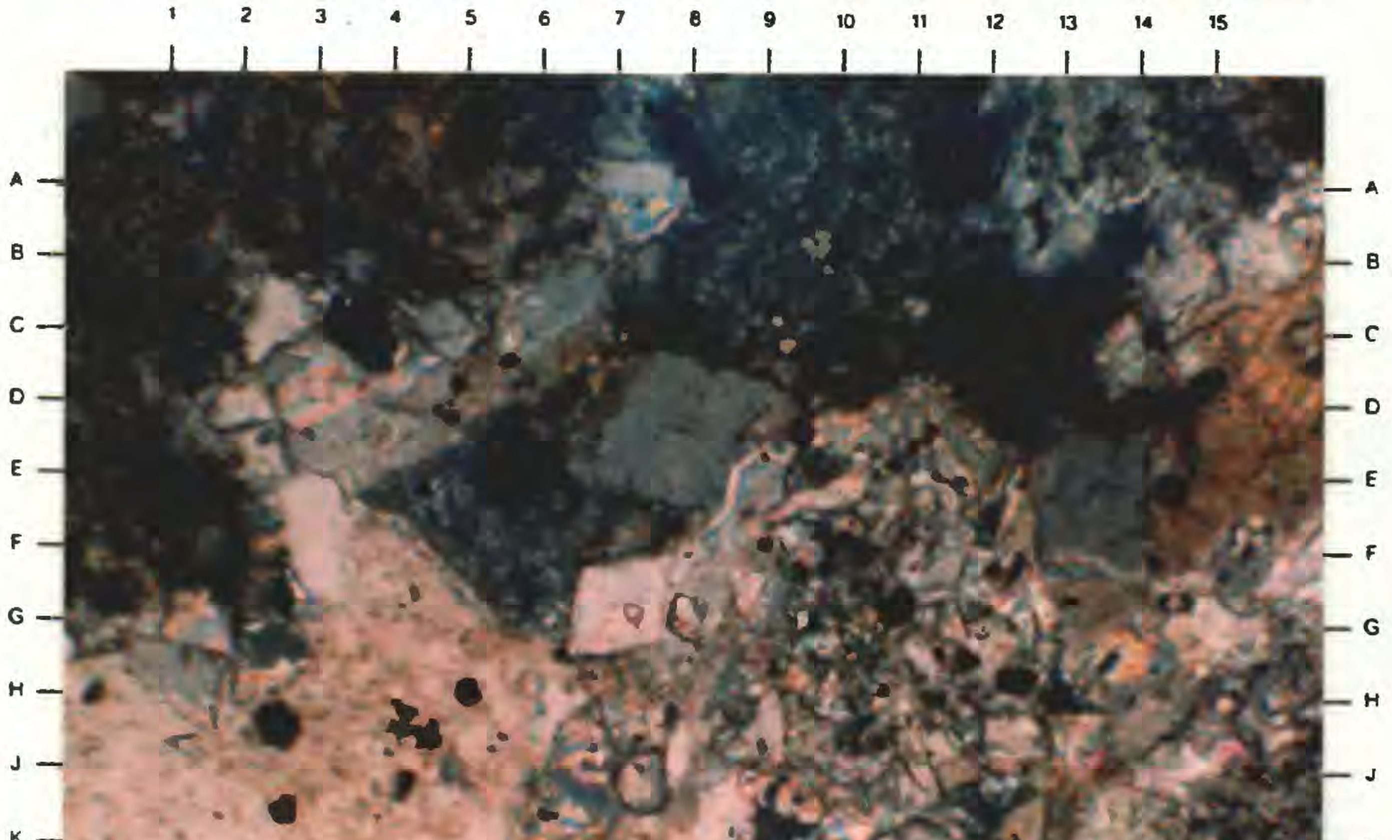
A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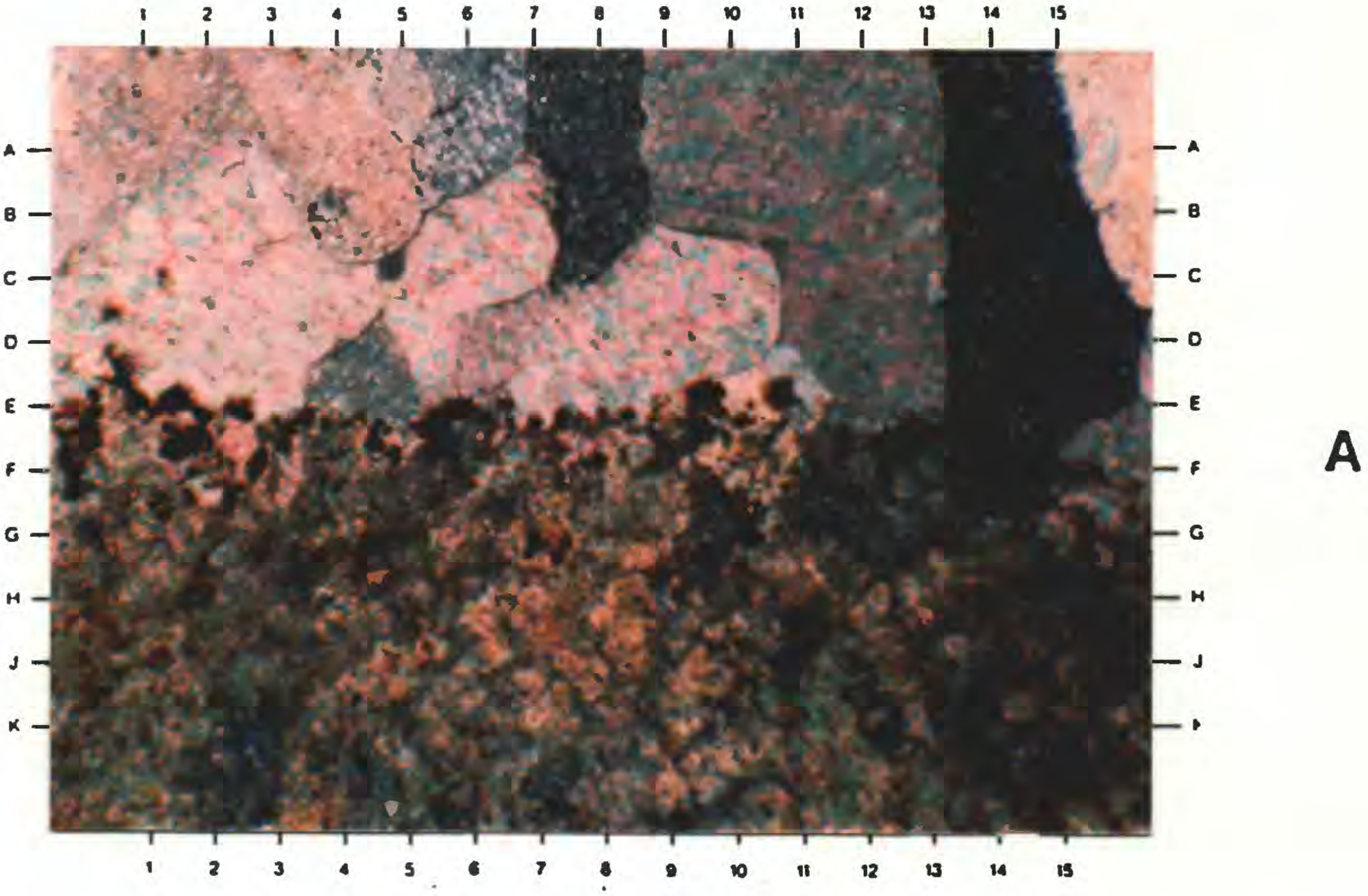
B



Hole 5 Depth 52.02 m

PLATE 21A

Boundary between neomorphic clasts (lower) and void-filling calcite cement (upper). The boundary is marked by organic material that originated within a micritic envelope. Partially crossed nicols, distance across photograph: 0.56 mm.

Hole 6 Depth ~5 m

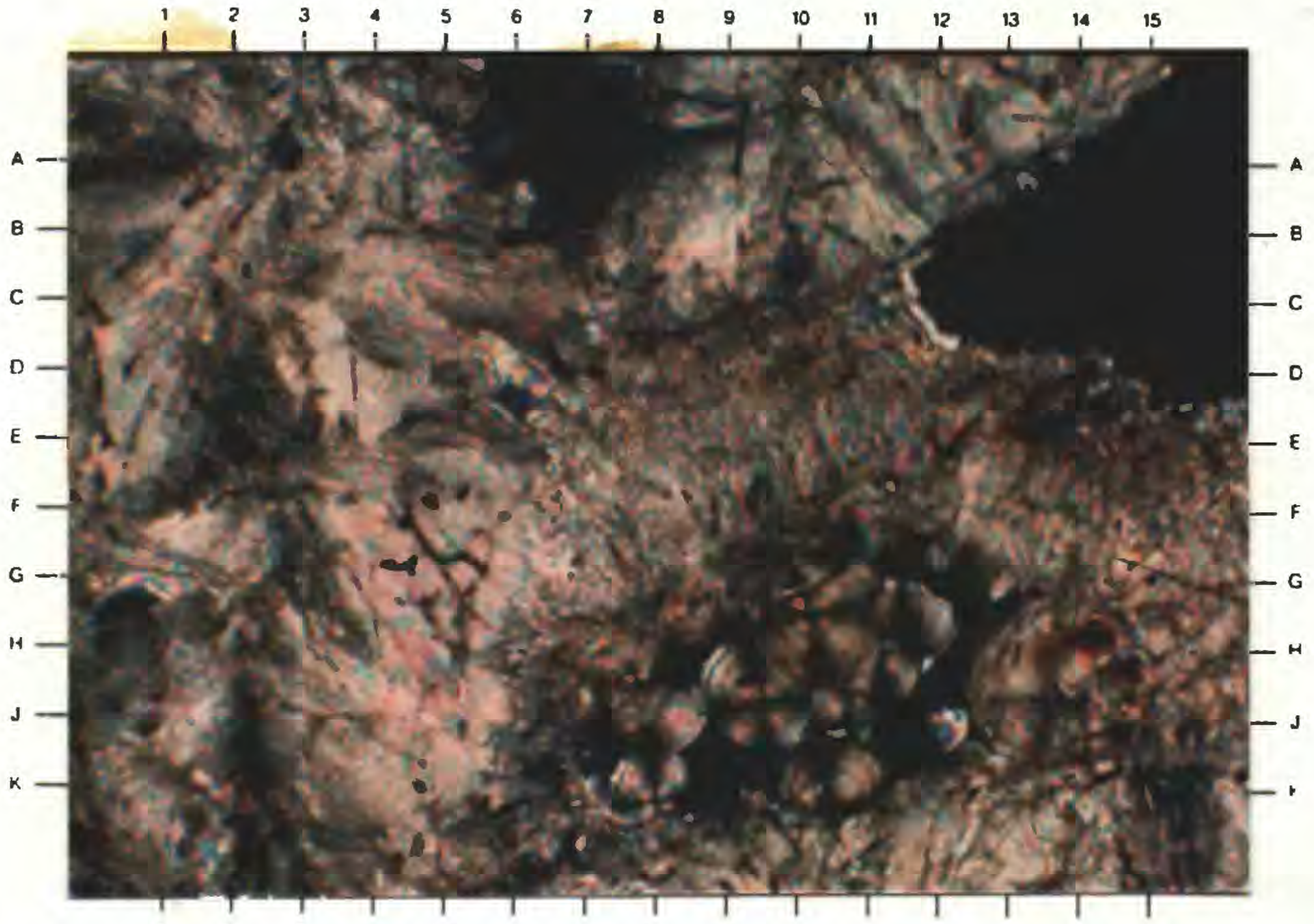
PLATE 22A

Unrecrystallized coral shows algal borings (G-5), a framework void filled with botryoidal aragonitic cement (H-10), and minor aragonitic rim cement developed in one void (C-14). Partially crossed nicols, distance across photograph: 0.56 mm.

Hole 6 Depth ~12.4 m

PLATE 22B

Echinoderm fragments floating in a bioclastic-rich micritic matrix. Echinoderm spines are seen in two orientations: perpendicular (A-6), and parallel (J-4) to the plane of the thin section. The bioclasts neomorphosed to calcite (F-9). Partially crossed nicols, distance across photograph: 2.3 mm.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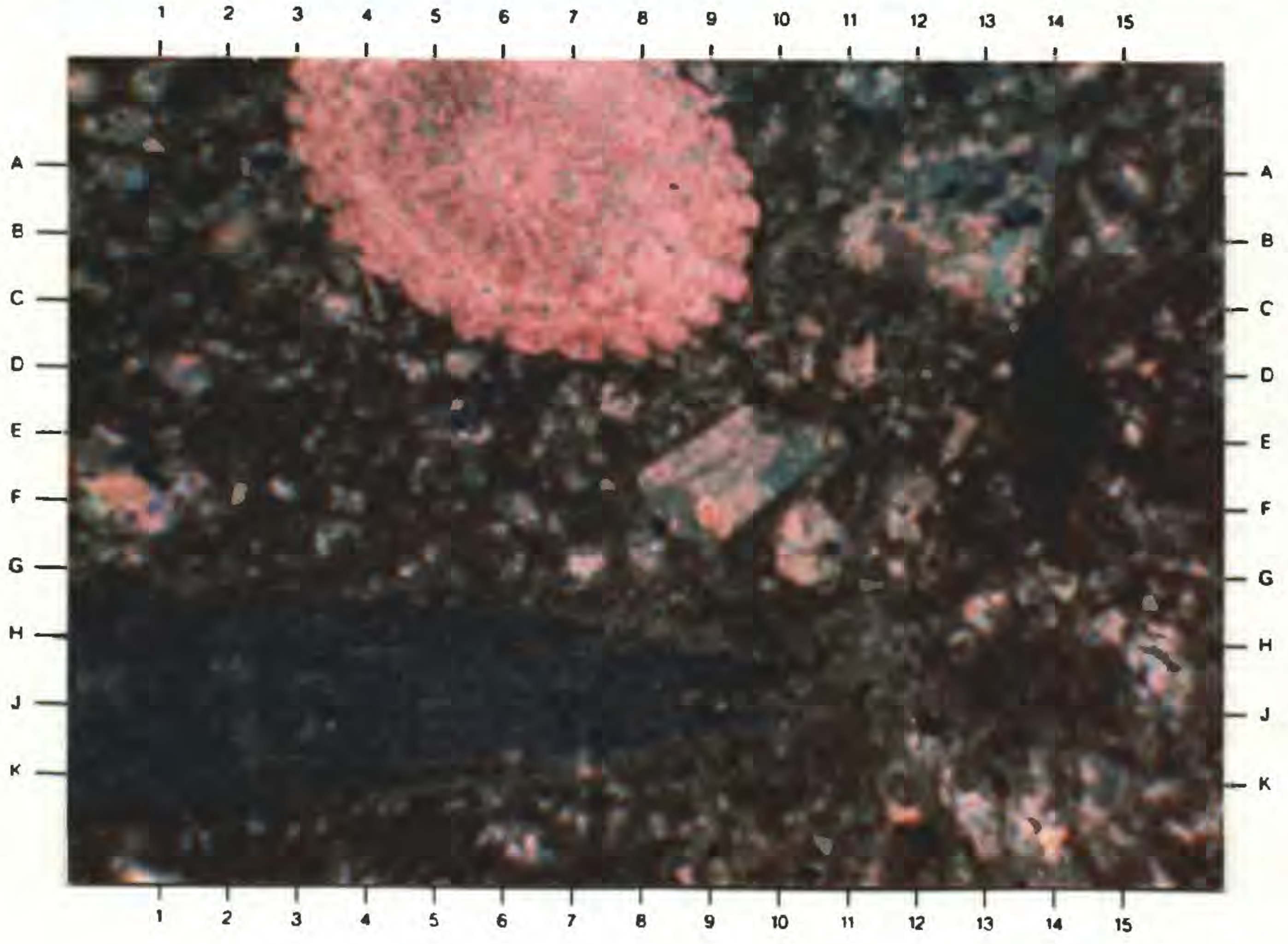
A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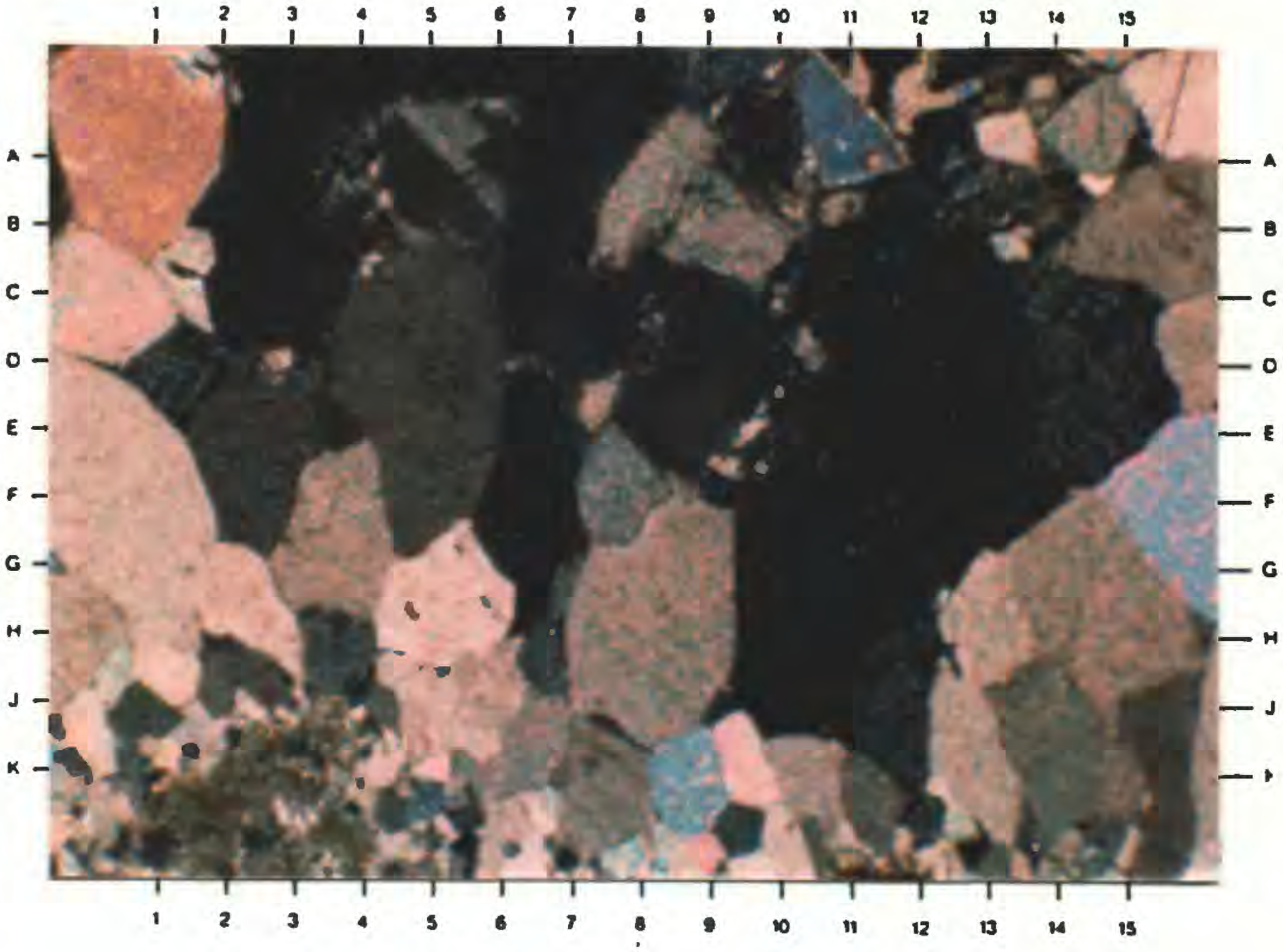
B



A

Hole 6 Depth ~17 m

PLATE 23A

Large equant calcite crystals typical of freshwater void-filling cement with partial dissolution of calcite crystals (A-6). Partially crossed nicols, distance across photograph: 2.3 mm.

Appendix 1

Mineralogy Tables

A. X-ray diffraction mineralogy of drill cores

B. Mole percentage $MgCO_3$ in carbonates

A. Mineralogy determined by x-ray diffraction for drill cores from Aitutaki Almost-Atoll, Cook Islands.

Sample No.[1]	Major[2]	Moderate	Minor or Trace
1A-4-345	Aragonite		Calcite
1A-5-497	Aragonite		Calcite
1A-5-501	Aragonite	Calcite	trace of other carbonates
1A-7-653	Aragonite		
1A-9-944	Calcite		Aragonite
1A-10-1085	Calcite		
1A-13-1507	Calcite	Aragonite	
1A-13-1530	Calcite		Aragonite
1A-14-1705	Calcite		
1A-14-1707	Calcite		
1A-16-1960-I	Calcite		
1A-16-1960-II	Calcite		
1A-16-2008A	Calcite		
1A-16-2008B	Calcite		
1A-19-2432	Calcite		
1A-21-2765	Calcite		
1A-21-2773	Calcite		
1A-23-3120A	Kaolinite	Goethite Anatase	Lepidocrocite Smectite
1A-23-3120B	Kaolinite	Anatase	
1A-23-3120C	Magnetite	Kaolinite	
1A-24-3251	Calcite		
1A-25-3295-I	Calcite		
1A-25-3295-II	Pyroxene	Calcite	

Sample No.[1]	Major[2]	Moderate	Minor or Trace
1A-25-3295-III	Calcite Pyroxene	Goethite	Smectite Mixed-layer clay minerals
1A-25-3295-IV	Pyroxene	Calcite Smectite	Mixed-layer clay minerals
1A-25-3295-V	Pyroxene	Plagioclase Calcite	Smectite Mixed-layer clay minerals Celadonite?
1A-25-3306	Calcite		Smectite
1A-25-3330	Magnetite	Smectite Goethite Calcite Kaolinite	Mixed-layer clay minerals Celadonite? Apatite?
1A-26-3487	Magnetite	Smectite Goethite	Kaolinite Calcite Celadonite Mixed-layer clay mimerals Pyroxene Apatite? Maghemite?
1A-26-3498	Calcite	Magnetite Goethite Smectite	Mixed-layer clay minerals Kaolinite Plagioclase Pyroxene Apatite? Maghemite?
1A-26-3531	Magnetite	Calcite Smectite Goethite Pyroxene	Mixed-layer clay minerals Kaolinite Plagioclase Apatite? Maghemite?
1A-26-3545	Magnetite	Goethite Smectite Plagioclase Pyroxene Calcite	Apatite? Celadonite? Maghemite?

Sample No.[1]	Major[2]	Moderate	Minor or Trace
1A-26-3547	Calcite	Magnetite Pyroxene Plagioclase Smectite Goethite	Celadonite? Apatite?
1A-26-3549	Calcite	Magnetite Pyroxene Plagioclase Smectite Goethite	Mixed-layer clay minerals Apatite?
1A-28-3644	Pyroxene	Calcite	Smectite
1A-28-3653	Magnetite Pyroxene	Smectite Plagioclase Goethite	Mixed-layer clay minerals Apatite? Maghemite?
1A-30-3825	Calcite		
1A-30-3873	Magnetite Pyroxene Plagioclase	Smectite Goethite	Hematite? Apatite?
2-1-6	Aragonite		Calcite
2-1-32	Aragonite Calcite		
2-6-710	Aragonite		Calcite
2-7-915	Aragonite Calcite		
2-8-1053	Calcite		
2-8-1073-I	Calcite		
2-8-1073-II	Calcite		
2-10-1355	Calcite		
2-14-1926	Calcite		
2-14-1995	Calcite		
2-16-2350	Calcite		
2-16-2357	Calcite		
2-17-2433	Calcite		

Sample No.[1]	Major[2]	Moderate	Minor or Trace
2-18-2620	Calcite		
2-19-2717	Calcite		
2-20-2985	Lepidocrocite Goethite	Nordstrandite[3] Anatase	
2-21-3070	Goethite Nordstrandite	Magnetite Lepidocrocite Anatase	Kaolinite
2-23-3267	Calcite		
2-25-3529	Calcite		
2-27-3835	Calcite		Dolomite
2-29-4150	Dolomite[4]		
2-29-4155	Dolomite		
2-30-4316	Dolomite	Hematite	Lepidocrocite
2-30-4317	Dolomite		
2-32-4590	Dolomite		Calcite
2-32-4648	Calcite		
2-33-4760	Dolomite		
2-33-4809	Dolomite		Calcite?
2-33-4814	Dolomite		
2-37-5321	Dolomite		
2-37-5325	Dolomite		
2-40-5850	Dolomite		
2-41-6008A	Dolomite		
2-41-6008B	Dolomite		
2-41-6008C	Dolomite		
2-43-6179	Calcite		Dolomite
2-44-6395	Dolomite		Lepidocrocite Hematite

Sample No.[1]	Major[2]	Moderate	Minor or Trace
2-44-6432	Dolomite		
2-46-6756	Dolomite		Calcite
2-46-6758	Dolomite		Lepidocrocite Hematite?
2-47-6876	Dolomite		
2-47-6900	Dolomite		
2-47-6910	Dolomite		
3-1-7	Aragonite		
3-1-50	Aragonite		
3-1-72-I	Aragonite Calcite		
3-1-72-II	Aragonite	Calcite	
3-1-72-III	Aragonite		Calcite
3-4A-650	Aragonite	Calcite	
3-5A-799	Aragonite	Calcite	
3-7-1070	Calcite		Aragonite
3-7-1075	Calcite		
3-9A-1420	Calcite	Goethite Kaolinite Magnetite	Nordstrandite Anatase Hematite?
3-10A-1585	Goethite	Kaolinite Nordstrandite Anatase	Lepidocrocite Magnetite Hematite
3-12A-1865	Goethite Kaolinite Magnetite	Anatase	Nordstrandite
3-13A-2015	Kaolinite Magnetite Goethite	Anatase	Nordstrandite Analcime?
3-16A-2472	Kaolinite Magnetite Goethite	Anatase	

Sample No.[1]	Major[2]	Moderate	Minor or Trace
3-19A-2922	Kaolinite Goethite Magnetite	Anatase	
3-20A-3073	Kaolinite Goethite Magnetite		Anatase
3-23-3469	Pyroxene Plagioclase	Smectite Olivine	
3-24A-3690	Goethite Magnetite Pyroxene	Plagioclase K-feldspar Smectite	Mixed-layer clay minerals? Apatite?
3-24-3693	Pyroxene	Magnetite Celadonite K-feldspar Goethite Smectite	Apatite
3-25-3741	Pyroxene	Plagioclase K-feldspar Olivine	Smectite Apatite?
3-25-3778	Pyroxene	Plagioclase K-feldspar Olivine	Smectite Apatite?
3-25-3787	Smectite		
3-26-3872	Calcite		
3-26-3887	Pyroxene	K-feldspar Plagioclase Olivine	Smectite Kaolinite Amphibole
3-26-3893	Calcite		Smectite Celadonite Amphibole
3-26-3938	Goethite Smectite Pyroxene Magnetite	Plagioclase	Calcite Hematite Mixed-layer clay minerals? Apatite?
4-2-116	Aragonite		Calcite
4-3-149	Aragonite		Calcite?
4-7-705	Aragonite		Calcite?

Sample No.[1]	Major[2]	Moderate	Minor or Trace
4A-4-570	Aragonite		Calcite?
4A-4-587	Aragonite		Calcite
4A-5-710	Calcite	Aragonite	
4A-6-879	Calcite	Aragonite	
4A-7-1019	Calcite		Aragonite
4A-8-1154	Calcite		
4A-8-1159	Calcite		
4A-9-1310	Calcite		
4A-10-1444	Calcite		
4A-12-1764	Calcite		
4A-15-2258	Calcite		
4A-15-2275	Calcite		
4A-18-2747a	Calcite		Hematite Magnetite Smectite
4A-18-2747b	Calcite		Hematite Magnetite Smectite
4A-19-2853	Calcite	Goethite Magnetite Smectite Hematite Pyroxene Apatite Mixed-layer clay minerals	
4A-19-2863	Pyroxene	Olivine Plagioclase Natrolite/Thomsonite Anatase	Kaolinite Smectite K-feldspar?
4A-19-2881	Pyroxene	Natrolite/Mesolite/Thomsonite Olivine	Kaolinite Smectite

Sample No.[1]	Major[2]	Moderate	Minor or Trace
4A-20-2945	Pyroxene	Natrolite/ Thomsonite Olivine	Kaolinite Smectite
4A-20-2966	Pyroxene Calcite	Natrolite/ Thomsonite	
4A-20-3034	Natrolite/ Mesolite/ Thomsonite		Kaolinite
5-1-4-305	Aragonite	Calcite	
5-1-4-315	Aragonite	Calcite	
5-2-5-950	Aragonite	Calcite	
5-8-1693	Aragonite Calcite		
5-9A-1934	Aragonite	Calcite	
5-9A-1934B	Aragonite Calcite		
5-10A-2083	Aragonite	Mg-Calcite Calcite	Pyrite Halite Kaolinite Gypsum Goethite?
5-11a-2230	Pyrite	Halite Kaolinite	Gypsum Anhydrite?
5-12A-2395	Kaolinite Goethite Magnetite	Nordstrandite Calcite	Analcime?
5-13-2507	Calcite		
5-14A-2714	Goethite	Nordstrandite Kaolinite	Magnetite
5-16-2970	Kaolinite Goethite Magnetite		Analcime?
5-19A-3477	Smectite Goethite Kaolinite	Mixed-layer clay minerals	Siderite?

Sample No.[1]	Major[2]	Moderate	Minor or Trace
5-22A-3918	Smectite Goethite	Celadonite Magnetite Hematite	
5-26-4468	Celadonite	Goethite Smectite Magnetite Apatite Mixed-layer clay minerals	Hematite? Kaolinite?
5-27-4640	Pyroxene	Calcite Smectite	Celadonite Magnetite Olivine Goethite Apatite Plagioclase? K-feldspar? Natrolite?
5-28-4764	Celadonite Pyroxene Magnetite Goethite Smectite	Apatite Plagioclase K-feldspar?	Hematite? Natrolite?
5-28-4776	Calcite		Dolomite?
5-29-4922	Calcite		Dolomite?
5-31-5202	Calcite	Dolomite	
5-31-5211	Calcite		
6-1-488	Aragonite		Calcite Mg-Calcite
6-2-693	Aragonite		Calcite
6-3-775-I	Calcite Aragonite Mg-Calcite		
6-3-775-II	Mg-Calcite Aragonite	Calcite	
6-3-779	Calcite Aragonite	Mg-Calcite	
6-4-929	Calcite		Aragonite?
6-5-1085	Calcite		Aragonite?

Sample No.[1]	Major[2]	Moderate	Minor or Trace
6-6-1244	Calcite		
6-9-1708a	Calcite	Kaolinite Goethite Magnetite	
6-9-1708b	Calcite		Kaolinite Goethite
6-11a-1993	Calcite		Kaolinite Goethite Magnetite?
6-12-2040	Calcite		Kaolinite Goethite Magnetite? Apatite?
6-12-2054	Pyroxene	Plagioclase K-feldspar Olivine Smectite	Kaolinite Amphibole Natrolite? Analcime?
6-13-2146	Calcite		Kaolinite Smectite Goethite Magnetite?
6-13-2160	Calcite		
6-14-2308	Calcite		
6-16-2605	Calcite		
6-17-2657	Calcite		
6-17-2660	Calcite		
6-18-2752	Calcite		
6-18-2763	Calcite		
6-19-2902	Calcite		

Sample No.[1]	Major[2]	Moderate	Minor or Trace
6-19-2910	Calcite		
6-19-2934	Calcite		

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[1] First number in sample number is hole number; second number is core number; third number is distance in centimeters from top of hole (seafloor). In some cores recovery was small and the core position in the hole was arbitrarily placed, so the third number is as we wrote before. This is common for samples in Hole 6 and for four samples in Hole 5.

[2] Roughly, major is >25%, moderate is 5-25%, and minor or trace is <5% (weight percent).

[3] Formula for nordstrandite is $Al(OH)_3$.

[4] Dolomite is protodolomite with 3 to 10 mole % excess $CaCO_3$ and broad and weak ordering x-ray reflections at 2.41 Å and 2.54 Å.

B. Mole percentage $MgCO_3$ in carbonates from Aitutaki, Cook Islands.

Sample No.	Mole % $MgCO_3$	Mineralogy	Comments
1A-10-1085	1	Calcite	
1A-13-1507	1	Calcite	
1A-13-1530	1	Calcite	
1A-14-1705	0	Calcite	
1A-14-1707	0	Calcite	
1A-16-1960-I	0	Calcite	
1A-16-1960-II	0	Calcite	
1A-16-2008A	0	Calcite	
1A-16-2008B	0	Calcite	
1A-19-2432	0	Calcite	
1A-21-2765	0	Calcite	
1A-21-2773	1	Calcite	
1A-24-3251	1	Calcite	
1A-25-3306	1	Calcite	
1A-30-3825	0.5	Calcite	
2-8-1073-I	1	Calcite	
2-8-1073-II	1	Calcite	
2-10-1355	1.5	Calcite	
2-14-1926	0	Calcite	
2-14-1995	0	Calcite	
2-16-2350	0	Calcite	
2-16-2357	0	Calcite	
2-17-2433	0	Calcite	
2-18-2620	0	Calcite	
2-19-2717	0.5	Calcite	
2-23-3267	0	Calcite	
2-25-3529	0	Calcite	
2-27-3835	0.5	Calcite	trace Dolomite
2-29-4150	42	Dolomite[1]	
2-29-4155	43	Dolomite	
2-30-4317	41	Dolomite	
2-32-4590	42	Dolomite	dolomite (major)
2-32-4590	1	Calcite	calcite (minor)
2-32-4648	1	Calcite	
2-33-4760	43	Dolomite	
2-33-4809	41	Dolomite	
2-33-4814	42	Dolomite	
2-37-5321	47	Dolomite	
2-37-5325	47	Dolomite	
2-41-6008A	41	Dolomite	
2-41-6008B	42	Dolomite	
2-41-6008C	44	Dolomite	

B. (continued)

Sample No.	Mole % $MgCO_3$	Mineralogy	Comments
2-43-6179	1	Calcite	trace Dolomite
2-44-6432	41	Dolomite	
2-46-6756	40	Dolomite	
2-47-6876	41	Dolomite	
2-47-6910	42	Dolomite	
5-31-5202	1.5	Calcite	calcite (major)
5-31-5202	43	Dolomite	dolomite (moderate)
5-31-5211	1	Calcite	
6-14-2308	0	Calcite	
6-16-2605	0	Calcite	
6-17-2657	0	Calcite	
6-17-2660	0	Calcite	
6-18-2763	0	Calcite	

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[1] All dolomites are protodolomites as defined by excess mole percentages of $CaCO_3$ and by weak and broad x-ray reflections at 2.41 Å and 2.54 Å.

Appendix 2

Chemical Composition Tables

A. Composition of carbonate deposits
B. Composition of volcanogenic deposits
C. Carbon and sulfur compositions

A. Chemical composition of carbonate rocks and sediments from Aitutaki, Cook Islands.

	1A-4-345	1A-10-1085	1A-16-1960	1A-21-2765	2-1-32	2-8-1073	2-14-1926	2-18-2620	2-25-3529	2-30-4316[1]
SiO_2 (wt. %)	<0.10	0.66	0.40	0.54	0.47	1.31	0.49	0.32	0.22	<0.1
Al_2O_3	0.21	0.23	0.35	1.01	0.28	0.19	0.25	0.30	0.14	0.35
Fe_2O_3	—	—	0.08	0.30	—	—	—	0.10	<0.04	17.5*
FeO	3.00	0.05	<0.02	0.05	0.07	0.05	0.08	0.05	<0.02	N/A
MgO	1.58	0.92	0.38	0.48	1.94	0.95	0.35	0.42	0.69	13.0
CaO	52.4	55.6	56.3	55.2	52.3	55.1	56.6	56.3	56.4	27.9
Na_2O	0.40	0.12	0.07	0.12	0.34	0.08	0.07	0.05	0.07	0.32‡
K_2O	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.05
TiO_2	<0.02	0.01	<0.02	0.19	0.02	<0.02	0.02	<0.02	0.01	<0.02
P_2O_5	0.05	0.07	0.06	0.17	0.05	0.09	0.08	0.08	0.06	0.30
MnO‡	0.001	0.004	0.003	0.008	0.001	0.001	0.001	0.002	0.001	<0.02
H_2O^-	0.22	0.01	0.01	0.06	0.21	0.02	0.05	0.06	0.02	N/A
H_2O^+	1.46	0.25	0.28	0.71	1.42	0.23	0.46	0.47	0.31	N/A
CO_2	41.3	44.8	44.6	43.9	44.2	44.5	44.9	45.2	45.0	N/A
LOI	44.8	43.7	43.2	43.2	44.3	42.9	43.6	43.5	43.8	41.07
Total †	102.44	101.36	100.84	101.27	99.77	101.17	101.54	101.12	101.39	101.44
Ba (ppm)	9	8	10	16	22	8	10	5	5	<20
Ce	<4	<4	<4	10	<4	<4	<4	<4	<4	N/A
Co	1	2	2	3	1	2	2	2	1	20
Cr	3	9	11	30	6	7	7	10	4	140
Cu	2	2	2	3	2	2	3	2	2	17
La	<2	<2	<2	2	<2	<2	<2	<2	<2	N/A
Li	<2	<2	<2	3	<2	<2	<2	<2	<2	<50
Mo	<2	<2	<2	<2	<2	<2	<2	<2	<2	N/A
Nd	<4	<4	4	7	4	<4	4	4	<4	N/A
Ni	2	5	7	20	3	3	5	5	3	30
Sc	<2	<2	<2	3	<2	<2	<2	<2	<2	<10
Sr	6300	1000	640	900	6100	760	340	300	420	230
V	8	4	4	10	4	<2	<2	4	<2	290
Zn	4	4	6	8	2	3	8	5	4	N/A
Lithology	reefal limestone	gray and white reefal limestone	gray reefal limestone	gray-brown reefal limestone	reefal limestone	pale gray reefal limestone	reefal limestone	medium-brown reefal limestone	dense, white reefal limestone	reddish-brown hydrothermal iron hydroxide-rich dolostone

	2-30-4317[1]	2-32-4590	2-37-5321[2]	2-44-6395	2-44-6432	2-46-6758	2-47-6910	3-1-50	3-7-1075	4-2-116
SiO_2 (wt. %)	0.35	<0.10	<0.1	0.29	0.52	0.16	1.42	0.63	0.90	<0.10
Al_2O_3	<0.1	0.22	0.2	0.30	0.18	0.29	0.32	0.10	0.32	0.02
Fe_2O_3	0.44*	—	0.16	3.67	—	5.58	0.10	—	0.53	—
FeO	N/A	0.08	N/A	<0.02	0.08	0.06	0.08	0.09	0.22	0.11
MgO	17.4	18.4	19.3	19.1	18.6	18.0	18.3	0.41	0.59	0.59
CaO	34.8	35.1	32.1	31.8	34.9	31.8	34.4	53.4	54.8	54.0
Na_2O	<0.3	0.13	0.12	0.12	0.15	<0.15	0.13	0.53	<0.15	0.40
K_2O	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
TiO_2	<0.02	<0.02	0.02	0.01	0.01	<0.02	<0.02	<0.02	0.11	<0.02
P_2O_5	0.07	0.05	0.08	0.12	0.07	0.09	0.07	<0.05	0.11	0.02
MnO‡	<0.02	0.003	0.003	0.02	0.01	0.06	0.01	0.001	0.01	0.001
H_2O^-	N/A	0.05	0.18	0.16	0.11	0.15	0.09	0.31	0.16	0.15
H_2O^+	N/A	0.40	0.21	0.55	0.39	0.92	0.46	1.30	0.49	1.86
CO_2	N/A	47.3	46.8	46.2	48.0	45.2	47.5	43.3	43.3	43.8
LOI	46.30	46.7	47.1	45.4	46.4	44.7	45.7	44.6	42.8	44.3
Total †	99.86	100.68	99.08	100.83	100.92	100.74	100.53	99.76	100.89	99.44
Ba (ppm)	26	4	12	6	8	5	16	9	18	9
Ce	N/A	<4	<4	<4	<4	<4	<4	<4	7	<4
Co	3.8	<1	1	4	1	5	5	1	4	1
Cr	20	6	24	86	15	30	18	1	52	3
Cu	9.9	4	6	8	2	4	4	<1	4	6
La	N/A	<2	4	<2	<2	<2	<2	<2	<2	<2
Li	<50	2	2	<2	<2	<2	4	<2	3	<2
Mo	N/A	<2	<2	3	<2	6	<2	<2	<2	<2
Nd	N/A	<4	<4	<4	<4	<4	<4	<4	5	<4
Ni	9.1	3	5	9	3	5	12	<2	20	3
Sc	<10	<2	<2	<2	<2	<2	<2	<2	<2	<2
Sr	320	290	130	190	250	210	260	7200	1100	7300
V	21	8	2	60	3	57	3	<2	11	3
Zn	N/A	<2	<2	<2	<2	<2	<2	7	9	19
Lithology	mustard yellow hydrothermal iron-hydroxide-bearing dolostone beneath 4316	dense grayish-white dolostone	dolostone	orange-brown hydrothermal iron-hydroxide-bearing dolostone	grayish-white dense, dolostone	mottled brown-gray hydrothermal iron-hydroxide-bearing dolostone	dense, white dolostone with pink-white areas	white, reefal limestone	black reefal limestone fragments	cemented reefal debris, limestone

A. (continued)

	4A-6-879	4A-10-1444	4A-15-2258	5-1-4-315[2]	5-2-5-950[2]	5-31-5202[2]	6-1-488	6-8-779	6-16-2605[2]	6-19-2934[2]
SiO_2 (wt. %)	0.49	0.10	0.85	<0.1	<0.1	1.1	<0.10	0.90	<0.1	<0.1
Al_2O_3	0.38	0.23	0.35	0.11	0.09	0.8	0.02	0.56	0.1	0.2
Fe_2O_3	0.08	0.08	0.10	0.1	0.1	0.50	0.01	0.30	<0.1	<0.1
FeO	<0.02	<0.02	0.05	N/A	N/A	N/A	<0.02	0.07	N/A	N/A
MgO	0.77	0.86	0.65	2.1	1.8	5.5	0.40	2.71	0.45	0.50
CaO	55.3	55.8	55.8	52.2	52.5	47.7	54.2	51.6	56.3	56.0
Na_2O	<0.15	0.08	0.07	0.40	0.45	0.24	0.49	<0.15	0.12	0.11
K_2O	<0.02	<0.02	<0.02	<0.05	<0.05	<0.05	<0.02	<0.02	<0.05	<0.05
TiO_2	0.03	<0.02	0.05	0.02	0.02	0.12	<0.02	0.06	0.02	0.02
P_2O_5	0.06	0.1	0.08	0.10	0.10	0.24	0.01	0.12	0.04	0.08
MnO‡	0.002	0.004	0.004	0.002	0.001	0.19	0.001	0.007	0.006	0.009
H_2O^-	0.06	0.03	0.04	0.62	0.39	0.36	0.16	0.35	0.08	0.10
H_2O^+	0.47	0.29	0.43	1.85	1.84	0.53	1.77	0.99	0.20	0.27
CO_2	44.9	45.2	44.8	41.4	42.1	42.8	44.2	43.9	43.6	43.6
LOI	43.8	43.8	43.5	45.0	44.6	43.9	44.4	43.5	43.6	43.7
Total †	100.91	101.05	101.00	100.03	99.66	100.29	99.53	99.83	100.64	100.62
Ba (ppm)	12	12	13	10	13	81	27	21	6	8
Ce	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4
Co	1	1	2	2	2	10	2	3	3	3
Cr	21	26	19	12	12	24	2	24	3	8
Cu	3	2	2	4	1	7	2	4	2	4
La	<2	<2	<2	5	5	7	<2	<2	6	6
Li	<2	<2	<2	<2	<2	7	<2	2	<2	<2
Mo	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Nd	<4	<4	<4	<4	<4	4	<4	<4	<4	<4
Ni	6	4	6	3	3	46	<2	15	11	5
Sc	<2	<2	<2	16	17	<2	<2	<2	<2	<2
Sr	1700	680	1200	5900	6400	180	7400	4000	220	380
V	4	2	4	4	4	15	<2	22	<2	<2
Zn	3	8	5	<2	<2	5	3	3	5	2
Lithology	grayish-white porous reefal limestone	grayish-white, reefal limetsone	gray and brown dense, reefal limestone fragments	silty carbonate mud	silty carbonate mud	dense recrystallized dolomitic limestone	reefal limestone	bioclastic limestone	reefal limestone	reefal limestone

All analyses were performed by U.S. Geological Survey analytical laboratories in Denver, Colorado and Menlo Park, California. Ten major oxides analyzed by wavelength dispersive x-ray fluorescence spectroscopy, Denver and Menlo Park. Analytical expertise provided by J. Taggart, A. Bartel, D. Siems, and R. Lerner. Some values for major elements and all minor and trace elements analyzed by inductively coupled plasma atomic emission spectroscopy, Denver. Analytical expertise provided by P. Briggs, and B. Anderson. FeO, CO_2, and water determined by wet chemical methods, Menlo Park. T. Fries, L. Espos, and S. Neil provided analytical expertise.

[1] Minor and trace elements analyzed by DC arc spectroscopy, Menlo Park. R. Lerner provided analytical expertise.

[2] The presence of organic materials prevented the accurate determination of FeO. Total Fe reported as Fe_2O_3. CO_2 value represents carbonate carbon only. See Table C in Appendix 2 for total carbon content.

— not detected.

N/A not analyzed.

* Total iron reported as Fe_2O_3.

† Totals based on LOI (loss on ignition) at 900 °C.

‡ Value reported is from emission spectroscopy data.

For all samples except 2-30-4316 and 2-30-4317 the following elements were analyzed but were below detection limits (in ppm): Ag <2; As <10 except 2-44-6395 and 2-46-6758 with 50 ppm; Au <8; Be <1; Bi <10; Cd <2 except 5-31-5202 with 2 ppm; Eu <2; Ga <4; Ho <4; Nb <4, except N/A for 6 samples; Pb <4; Sn <10; Ta <40; Th <4; U <100; Y <2 except 1A-21-2765 with 3 ppm; and Yb <1. For 2-30-4316 and 2-30-4317: As <200; Be <1.0; Cd <2.0; Ga <10; Y 16 and <10 respectively.

B. Chemical composition of volcanogenic rocks and sediments from Aitutaki, Cook Islands.

	1A-23-3120	1A-26-3487	1A-28-3653	1A-30-3873	2-21-3070	3-10A-1585	3-13A-2015
SiO_2 (wt. %)	28.4	31.9	35.5	40.4	8.82	17.3	22.4
Al_2O_3	23.5	18.6	13.8	16.7	24.6	23.8	23.1
Fe_2O_3	23.1	16.8	11.7	14.4	28.2	31.1	25.7
FeO	0.64	2.14	2.09	2.65	0.39	0.40	<0.02
MgO	0.89	1.53	2.70	4.13	3.96	1.00	0.70
CaO	0.29	5.66	11.5	3.11	1.74	0.43	0.38
Na_2O	1.34	1.23	1.64	1.60	1.70	1.02	1.22
K_2O	0.13	0.51	1.14	1.68	0.09	0.11	0.13
TiO_2	4.52	3.74	2.73	3.35	5.14	4.76	4.29
P_2O_5	0.47	1.13	0.79	0.93	1.89	1.38	1.20
MnO	0.07	0.11	0.21	0.23	0.02[†]	0.08	2.71
H_2O^-	3.66	5.28	4.78	4.26	3.17	3.10	3.64
H_2O^+	9.47	6.66	3.48	4.82	14.5	13.0	10.2
CO_2	0.22	2.91	6.30	0.09	2.12	0.81	0.47
LOI	16.5	16.7	16.4	10.6	22.9	18.9	18.1
Total[1]	99.85	100.05	100.20	99.78	99.45	100.28	99.93
As (ppm)	<10	<10	<10	<10	190	210	90
Ba	150	140	520	560	67	410	1200
Be	4	2	2	2	5	5	4
Cd	<2	3	3	3	4	3	2
Ce	42	110	96	120	270	250	220
Co	50	48	86	87	83	140	610
Cr	1300	1000	640	820	1800	1400	1200
Cu	61	78	55	69	63	69	150
Eu	2	5	4	5	7	8	7
Ga	39	31	24	27	28	34	54
La	29	67	52	69	170	140	140
Li	93	41	24	54	220	160	250
Mo	3	<2	<2	<2	20	11	6
Nb	64	31	39	41	140	100	100
Nd	21	63	52	68	120	120	100
Ni	670	510	390	480	1300	970	1200
Pb	16	10	9	14	40	23	18
Sc	47	31	24	30	58	49	47
Sr	230	160	390	400	1400	1400	1100
Th	16	11	8	11	33	26	31
V	320	220	170	190	400	370	380
Y	34	36	31	44	71	84	74
Yb	3	3	3	3	6	6	5
Zn	200	190	130	180	240	250	220
Lithology	dark gray altered tuff(?) with orange veins, pedogenic	dark gray completely altered volcanic rock, pedogenic	altered alkalic basalt with calcite veins	relatively fresh alkalic basalt	yellowish-brown pedogenic mud. Sinkhole or cave floor deposit.	brown, slightly sandy pedogenic mud	brown and black slightly silty pedogenic mud

B. (continued)

	3-16A-2472	3-20A-3073	3-23-3469	3-26-3887	4A-18-2747	4A-19-2863	4A-20-2945
SiO_2 (wt. %)	27.4	28.3	44.8	44.3	18.9	38.6	39.3
Al_2O_3	21.1	24.3	11.6	11.7	9.37	10.6	10.7
Fe_2O_3	22.6	18.4	3.06	3.86	10.0	6.85	6.30
FeO	0.31	0.27	8.23	6.97	0.61	5.36	6.04
MgO	1.01	0.58	12.1	12.5	1.48	12.9	12.6
CaO	0.54	1.05	10.4	11.1	28.5	13.2	13.4
Na_2O	1.80	1.16	3.22	2.90	0.82	2.10	2.44
K_2O	0.25	0.13	1.11	1.10	0.23	0.91	0.40
TiO_2	4.67	3.97	1.83	1.85	2.15	2.46	2.52
P_2O_5	1.18	2.77	0.89	0.83	1.00	1.09	1.13
MnO	0.39	0.11	0.17	0.16	0.10	0.18	0.19
H_2O^-	6.06	4.15	0.82	1.13	3.62	1.03	0.83
H_2O^+	8.76	12.3	1.46	1.62	3.99	4.31	4.62
CO_2	0.25	0.42	0.32	0.32	21.0	0.30	0.13
LOI	18.5	17.6	1.97	2.64	27.5	5.37	5.14
Total[1]	99.75	98.64	99.38	99.91	100.66	99.62	100.16
As (ppm)	30	30	<10	<10	<10	<10	<10
Ba	790	1900	660	880	430	1000	540
Be	4	4	1	1	2	2	2
Cd	2	<2	3	2	2	2	2
Ce	350	390	120	110	140	150	160
Co	72	59	61	60	48	66	64
Cr	820	1000	580	610	210	320	320
Cu	66	42	48	48	46	42	42
Eu	10	13	4	4	4	4	5
Ga	36	36	21	20	18	20	21
La	210	240	69	66	80	81	87
Li	64	69	12	11	38	13	14
Mo	<2	2	<2	<2	<2	2	<2
Nb	130	81	38	38	12	18	24
Nd	160	190	56	54	65	71	74
Ni	530	690	360	320	150	250	240
Pb	26	24	12	10	9	11	9
Sc	40	33	19	20	15	21	20
Sr	860	7100	1100	1000	620	1700	1700
Th	39	25	10	11	13	11	14
V	230	240	140	150	120	160	170
Y	75	100	28	28	28	29	31
Yb	6	5	2	2	2	2	2
Zn	220	230	110	110	110	120	120
Lithology	brown pedogenic mud	sandy brown pedogenic mud with goethite streaks	coarse-grained alkalic basalt	medium-grained alkalic basalt	very highly altered, calcite-veined alkalic basalt	moderately altered nephelinite	moderately altered nephelinite

B. (continued)

	5-11a-2230	5-12A-2395	5-16-2970	5-22A-3918	5-27-4640	6-9-1708	6-12-2054
SiO_2 (wt. %)	3.3	15.7	26.0	30.8	38.2	7.84	43.7
Al_2O_3	4.90	21.0	23.0	18.2	13.1	4.45	11.9
Fe_2O_3	N/A	22.1*	21.4	18.6	11.0	2.22	2.73
FeO	13.5‡	N/A	0.46	0.74	2.60	0.04	7.99
MgO	1.1	1.0	0.6	1.6	5.7	0.45	11.9
CaO	1.32	7.48	0.26	2.12	10.3	47.1	10.9
Na_2O	3.3	1.5	0.80	1.1	1.1	0.23	3.3
K_2O	0.14	0.10	0.14	0.26	0.98	0.03	1.06
TiO_2	0.94	4.50	3.64	3.66	2.52	0.56	1.80
P_2O_5	0.92	1.62	1.08	1.38	0.76	0.06	0.80
MnO	0.07	0.22	0.07	0.28	0.18	<0.02	0.16
H_2O^-	11.96	N/A	9.06	13.21	6.55	0.66	1.12
H_2O^+	21.45	N/A	9.02	6.47	3.82	2.29	1.41
CO_2	N/A‡	N/A	0.17	0.20	2.85	37.2	0.64
LOI	70.7	23.1	21.3	20.9	13.2	38.4	2.88
Total[1]	100.19	98.32	98.75	99.14	99.59	100.88	99.12
As (ppm)	50	110	30	<10	<10	<10	<10
Ba	210	710	570	210	630	12	740
Be	1	3	4	2	2	<1	2
Cd	<2	4	<2	<2	2	<2	<2
Ce	71	260	140	130	92	20	120
Co	110	100	58	180	64	10	60
Cr	290	1000	1100	850	790	220	500
Cu	52	56	60	75	52	22	48
Eu	<2	8	5	5	4	2	4
Ga	8	29	32	28	22	6	20
La	43	170	70	80	58	15	70
Li	31	140	77	37	31	33	14
Mo	3	8	<2	<2	<2	<2	<2
Nb	N/A	N/A	N/A	N/A	N/A	11	N/A
Nd	32	130	61	64	47	21	55
Ni	330	640	690	810	570	84	340
Pb	12	23	10	9	7	4	8
Sc	12	41	44	32	24	11	21
Sr	910	2200	1600	180	490	230	1000
Th	8	28	21	14	10	6	11
V	120	310	310	220	180	43	150
Y	20	77	41	36	28	26	26
Yb	2	6	5	4	3	2	2
Zn	110	170	190	220	140	21	100
Lithology	greenish-black organic-rich mud	dark yellow-brown silty pedogenic mud	gray altered pyroclastic(?) deposit, pedogenic	very altered basalt(?), pedogenic	alkalic basalt	yellowish-brown mottled highly altered volcaniclastic rock(?), pedogenic	fresh alkalic basalt

All analyses were performed by U.S. Geological Survey analytical laboratories in Denver, Colorado and Menlo Park, California. Ten major oxides analyzed by wavelength dispersive x-ray fluorescence spectroscopy, Denver and Menlo Park. Analytical expertise provided by J. Taggart, A. Bartel, D. Siems, D. Vivit, and M. Dyslin. Minor and trace elements analyzed by inductively coupled plasma atomic emission spectroscopy, Denver. Analytical expertise provided by P. Briggs, and B. Anderson. FeO, CO_2, and water determined by wet chemical methods, Menlo Park. T. Fries, L. Espos, and S. Neil provided analytical expertise.

[1] Totals based on LOI (loss on ignition) at 900 °C.

N/A not analyzed.

* Total iron reported as Fe_2O_3.

† Value reported is from emission spectroscopy data.

‡ Total iron reported as FeS_2. Carbon present is primarily organic. See Table C, Appendix 2 for sulfur and carbon contents and Table A, Appendix 1 for mineralogy.

The following elements were analyzed for but were below detection limits: Ag <2; Au <8; Bi <10; Ho <4; Sn <10; Ta <40; U <100.

C. Carbon analysis of various rock types and sulfur analysis from an organic-rich mud from Aitutaki, Cook Islands. Values are in weight percent.

Sample No.	Total C	Organic C	Carbonate C	Total S	Lithology
2-37-5321	13.1	0.26	12.8	—	reefal limestone
5-1-4-315	12.0	0.73	11.3	—	silty carbonate mud
5-2-5-950	11.8	0.29	11.5	—	silty carbonate mud
5-11a-2230	32.5	32.5	<0.01	9.69	greenish-black organic-rich mud
5-16-2970	0.05	0.05	<0.01	—	gray volcaniclastic and pedogenic mud
5-22A-3918	0.05	0.02	0.03	—	volcaniclastic and pedogenic mud
5-27-4640	0.78	0.04	0.74	—	basalt
5-31-5202	12.2	0.44	11.7	—	dense limestone
6-12-2054	0.17	0.02	0.15	—	basalt
6-16-2605	12.3	0.40	11.9	—	reefal limestone
6-19-2934	12.1	0.25	11.9	—	reefal limestone

Total C and total S determined by infrared absorption spectrophotometry. Carbonate carbon determined by coulometric titration. Organic carbon determined by difference. Analyses performed at U.S. Geological Survey analytical laboratories, Menlo Park, California. T. Fries and S. Neil provided analytical expertise.

Appendix 3

Carbon, oxygen, and deuterium isotopic compositions of carbonates

Appendix 3. Carbon, oxygen, and deuterium isotopic compositions of calcite cements and veins, aragonite muds, and dolomite from Aitutaki, Cook Islands.

Sample No.	$\delta^{13}C$ PDB	$\delta^{18}O$ SMOW	δD SMOW	Mineralogy	Sample Description
1A-14-1705	-12.0	24.8	—	Calcite	coarse-grained sparry calcite cement
1A-14-1707	-9.1	24.7	—	Calcite	same as above
1A-16-2008A	-10.7	25.0	—	Calcite	dog-tooth spar calcite layer above 2008B
1A-16-2008B	-11.3	24.7	—	Calcite	sparry calcite layer
1A-19-2432	-10.1	24.9	—	Calcite	coarse-grained dog-tooth spar calcite in vug
1A-24-3251	-10.4	24.9	—	Calcite	sparry calcite layer within tuff section
1A-25-3306	-10.4	25.0	—	Calcite	sparry calcite layer below basalt and above tuff
1A-30-3825	-11.2	25.2	—	Calcite	calcite layer within basalt
2-14-1995	-4.0	24.9	—	Calcite	sparry calcite layers with dog-tooth spar filled vugs
2-16-2350	-10.9	24.9	—	Calcite	up to 3-cm-long, calcite crystals
2-16-2357	-11.0	25.1	—	Calcite	same as above
2-17-2433	-10.9	25.2	—	Calcite	sparry calcite layer
2-23-3267	-10.6	24.6	—	Calcite	sparry calcite layer
2-27-3835	-10.6	25.1	—	Calcite	sparry calcite layer
2-32-4648-I	-9.1	25.3	—	Calcite	up to 2-cm-long sparry calcite crystals
2-32-4648-II	-10.1	25.2	—	Calcite	same as above
2-32-4648-III	-10.7	26.6	-50	Calcite	same as above

Appendix 3. (continued)

Sample No.	$\delta^{13}C$ PDB	$\delta^{18}O$ SMOW	δD SMOW	Mineralogy	Sample Description
2-33-4760	+2.5	34.1	-27	Dolomite	dolomite
2-40-5850	+2.8	33.6	—	Dolomite	dolomite
2-43-6179	-8.8	25.8	—	Calcite	sparry calcite layer
2-47-6900	+2.9	33.2	—	Dolomite	dolomite
4A-18-2747b	-11.7	25.3	—	Calcite	calcite veins in altered basalt
4A-20-2966	-14.7	25.5	—	Calcite	calcite filling basalt vesicles
5-1-4-315	+3.1	29.3	—	Aragonite Calcite	silty carbonate mud
5-2-5-950	+2.9	29.3	—	Aragonite Calcite	silty carbonate mud
5-31-5211	-10.9	25.4	—	Calcite	sparry calcite
6-14-2308	-10.9	25.1	—	Calcite	calcite replaced reefal limestone
6-16-2605	-9.8	25.2	—	Calcite	sparry calcite layer
6-17-2657	-9.3	25.3	—	Calcite	sparry calcite layer
6-17-2660	-8.7	25.2	—	Calcite	sparry calcite layer
6-18-2763	-10.4	24.8	—	Calcite	sparry calcite layer
Average Calcite	-11.0	25.1			
Average Aragonite	+3.0	29.3			
Average Dolomite	+2.7	33.6			
Average Dolomite	—	31.1*			

* Corrected for mole percentage $MgCO_3$ (Tarutani et al., 1969).

Analyses performed at U.S. Geological Survey isotope laboratory by Doug White.

Appendix 4

Uranium and thorium compositions, and U-series apparent ages

Appendix 4. Uranium and thorium contents and U-series apparent ages of coral from Aitutaki, Cook Islands.

Lab No.	Field No.	U ppm	Th ppm	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	U/Th age 1,000 years	Corrected age 1,000 years	Coral Types and Comments	Mineralogy (XRD)*
637	1A-5-497	4.268±0.150	1.207±0.154	1.157±0.044	1.108±0.187	0.089±0.011	$10.0^{+1.3}_{-1.2}$	$1.0^{+1.2}_{-1.0}$	*Porites*	A(c)
638	1A-5-501	—	—	—	—	—	recent	—	No Th detected	A(C)
639	1A-7-658	3.177±0.101	0.044±0.043	1.119±0.029	33.827±33.448	0.154±0.015	$18.1^{+1.9}_{-1.8}$	$17.7^{+1.9}_{-1.8}$	*Porites*	A
640	1A-13-1507	2.986±0.112	0.229±0.061	0.991±0.033	44.285±11.682	1.124±0.070	≥202	—	Recrystallized reefal debris	C(A)
642	2-1-6	5.331±0.261	0.142±0.048	1.243±0.053	3.813±1.395	0.020±0.004	3.0±0.4	2.2±0.4	Excess ^{235}U; *Porites*	A(c)
884	2-6-710	3.919±0.091	0.122±0.019	1.096±0.019	12.266±1.909	0.114±0.006	13.1±0.7	12.1±0.7	*Acropora*	A(c)
643	2-10-1355	2.033±0.090	0.079±0.025	1.068±0.052	70.905±22.130	0.852±0.048	$198.5^{+47.5}_{-31.0}$	$197.2^{+46.8}_{-30.1}$	*Diploastrea*	C
644	2-14-1937	1.365±0.054	0.078±0.028	1.094±0.050	57.261±20.800	0.977±0.050	≥247	—	Recrystallized *Acropora*	C
645	2-14-1955	1.483±0.078	0.135±0.044	1.015±0.058	33.657±12.641	1.177±0.093	≥175	—	*Acropora*	C
646	2-19-2717	0.223±0.037	0.049±0.048	1.909±0.375	14.460±14.630	0.542±0.109	$78.9^{+26.5}_{-20.6}$	$75.2^{+25.5}_{-19.8}$	Recrystallized *Porites* .sp	C
647	2-29-4154	1.687±0.110	0.156±0.048	1.065±0.068	30.760±9.551	0.871±0.077	$212.0^{+111.3}_{-49.8}$	$209.0^{+105.8}_{-47.6}$	Recrystallized *Porites*	D
648	2-29-4159	1.914±6.112	0.074±0.074	1.054±0.062	81.673±81.836	0.989±0.106	≥167	—	Recrystallized *Porites* sp.	D
649	2-37-5825	1.718±0.059	0.292±0.252	1.041±0.042	22.950±19.932	1.230±0.163	≥123	—	*Porites*	D
650	2-47-6876	0.560±0.038	0.165±0.165	0.927±0.085	10.548±10.797	1.100±0.269	≥60	—	U-leaching; cemented reefal debris	D
651	3-1-16	2.884±0.097	—	1.143±0.036	—	—	Recent	—	Excess ^{235}U; *Porites*	A
652	3-7-1070	4.657±0.149	0.448±0.087	1.200±0.034	17.223±3.344	0.454±0.028	$64.8^{+5.7}_{-5.3}$	$61.5^{+5.5}_{-5.1}$	Excess ^{235}U; *Pocillopora*	C(a)
653	3-9A-1420	12.942±1.044	48.832±5.318	1.129±0.118	1.960±0.241	2.152±0.229	>88	—	Volcaniclastic mud	—
654	4-3-179	2.694±0.065	—	1.109±0.025	—	—	Recent	—	Excess ^{235}U; *Favia* sp.	A(c?)
655	4A-4-574	6.430±0.198	0.288±0.288	1.109±0.029	1.301±1.719	0.017±0.015	1.9±1.7	0.4±1.7	Excess ^{235}U; *Leptoria*	A(c?)
656	4-7-705	2.620±0.097	0.228±0.228	1.170±0.042	3.773±4.000	0.092±0.034	$10.5^{+4.1}_{-4.0}$	$7.8^{+4.0}_{-3.9}$	*Psammocora*	A(c?)
657	4A-15-2275	2.642±0.107	0.285±0.285	1.056±0.045	26.566±26.753	0.892±0.148	≥135	—	*Favia*	C
658	5-13-2507	1.322±0.060	5.421±2.088	1.176±0.082	2.528±0.780	2.898±0.926	≥64	—	Anomalous Th values; Recrystallized	C
659	5-29-4922	0.880±0.072	0.252±0.252	1.194±0.130	14.60±14.60	1.202±0.247	≥88.4	—	Recrystallized, genus unknown	C(d?)
660	6-2-693	4.880±0.232	0.385±0.387	1.166±0.052	0.793±1.387	0.018±0.025	$1.9^{+2.9}_{-2.7}$	$0.2^{+2.8}_{-2.6}$	Excess ^{235}U; *Astropora*	A(c)
661	6-13-2160	0.991±0.063	0.050±0.042	1.342±0.703	64.781±54.209	0.807±0.064	$158.9^{+36.0}_{-25.9}$	$157.7^{+35.6}_{-25.3}$	Excess ^{235}U; Recrystallized *Porites*	C
662	6-18-2752	1.027±0.063	0.188±0.188	0.958±0.076	15.41±15.52	0.969±0.144	≥124	—	Excess ^{235}U; Recrystallized *Acropora*	C

*	Major	Moderate	Minor or Trace
Aragonite	A	(A)	(a)
Calcite	C	(C)	(c)
Dolomite	D	(D)	(d)